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The Role of Pigs in the Carbon Footprint of Red Meat in Canada

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ABSTRACT

Global livestock production is a major driver of climate change. Lumping beef and pork together as red meat masks important differences in their carbon footprints, land uses, and social status. These two red meat choices in Canada were compared by using a meta-model of the Unified Livestock Industry and Crop Emissions Estimation System (ULICEES). ULICEES calculated fossil CO_2, N_2O and CH_4 emissions for beef, dairy, pork, poultry, and sheep production in Canada, based on both the livestock and their supporting land base in 2001. The dynamic drivers of the meta-model were crop yields, breeding female populations, tillage practices, nitrogen fertilizer use, and the crop complex of each livestock industry. When the potential carbon sequestration in the land growing harvested perennial forage is credited to beef production, the CO_2e emissions offset does not reduce the carbon footprint of beef enough to match the lower carbon footprint of pork. Most of the land required to grow hay for beef would not be needed to feed a protein-equivalent pig population. In a hypothetical conversion of all beef production to pork production for 2021, 4.5 Mha of land under perennial forage was freed and 10.0 MtCO_2e per year was mitigated when that area was re-cultivated for annual crops—a GHG mitigation equal to 12% of the GHG emissions budget of Canadian agriculture. Leaving that area under a perennial ground cover mitigated 19.8 MtCO_2e per year, the equivalent of 23% of the sector's GHG emissions budget.

Keywords: Pigs; Beef Cows; Protein; Red Meat; Climate Change; Carbon Footprint; Land Use Change

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1. Introduction

There is wide acceptance that global livestock production is exceeding planetary boundaries [1–6], and that consumption of animal products is accelerating climate change [7, 8]. During the past decade, attention has shifted towards keeping food production within planetary boundaries and reducing over-consumption [1–6]. This worldview treats climate change as just one of many environmental degradation challenges along with nitrate leaching, biodiversity loss, and other issues. However, in 2018, the UN Secretary-General identified climate change as the defining issue of our time and added that the time to address this threat was very short [9]. Following this guidance, the scope of this analysis was limited to just the livestock-climate interface.

The 2023 United Nations Climate Change 28th Conference of the Parties (COP28) called upon all governments to develop effective Greenhouse Gas (GHG) mitigation measures for the agriculture sector [10]. The World Bank proposed cutting or redirecting subsidies that go to meat and dairy industries [11]. Denmark is planning to impose a tax on farmers based on the carbon footprint of livestock production [12]. Implementing these measures will require clear and accurate assessments of the GHG emissions from livestock [13, 14]. These assessments must also take soil carbon sequestration into account [15–17].

The Canadian livestock sector, to which almost $2 billion CAD was allocated by the Canadian government in 2021 [11], must achieve substantial GHG emission reductions. The three most consumed carcass products in Canada are chicken (broilers), beef and pork [18]. Beef and pork both used far more Canadian farmland in 2017 than was used for broiler production [19]. Canada is the 11th largest beef producer and the sixth largest pork producer in the world, with substantial contributions to the GDP [10]. These two industries contributed 30% and 7%, respectively, of the 84 $MtCO_2e$ emitted by the Canadian agriculture sector [20]. In many media reports and policy discussions regarding environmental impacts [8, 11, 21–24], beef and pork are typically lumped together as red meats, or simply "meats" (only excluding dairy and poultry). Although this lack of distinction is less frequent in the scientific literature, it is essential that scientific publications provide an easily interpreted illustration of the beef-pork carbon footprint difference. But this grouping masks important differences in these two commodities [25, 26]. Chicken has a substantially lower carbon footprint than either of these two red meats [11, 26, 27]. The carbon footprint of the animal quality protein derived from pulse crops is even lower than that of chicken [28].

A widely accepted view of the Canadian beef industry is that, unlike pig farming, it sequesters atmospheric carbon [15]. In reality, neither animal actually sequesters carbon; their respective populations are the result of how farmers use their land. Growing perennial forage avoids soil-exposing tillage and allows atmospheric carbon to be sequestered [16]. Most of the land needed to support beef cattle is used to grow perennial forage, which only ruminants can digest. Thus, cattle provide an economic incentive to maintain perennial ground cover. When the land is tilled for feed grains, that soil is exposed in the spring and fall, and some of its carbon is oxidised [29].

Estimates of the carbon footprints of beef and pork can vary considerably, largely depending on whether and how Soil Organic Carbon (SOC) and land use are taken into account. This paper will compare the carbon footprints of beef and pork and clarify the differences that will most affect GHG mitigation policy and consumer choices. While this analysis was focused on production rather than consumers [25], shifting production from high to low carbon footprint livestock products will depend on consumer acceptance. Therefore, the social and historical factors that could impede such consumer acceptance and meaningful GHG emission reductions will also be assessed. Although for some consumers humane treatment of farm animals is important, because animal welfare cannot be quantified in terms comparable to carbon footprint calculations, it was excluded from this analysis.

2. Background

2.1. Preliminary Canadian Livestock Carbon Footprint Estimates

The GHG emission budgets for dairy, beef, pork, poultry and sheep in Canada were estimated by Vergé et al. [30–34]. An important common element of these assessments was to link the GHG emissions by these commodities to their supporting land bases through their Livestock Crop Complexes (LCC), defined as the land required to grow the feed for a given livestock population [35]. In a summary of the first four commodity assessments, Dyer et al. [25] showed that the highest GHG emissions came from beef, whereas the two non-ruminants had the lowest of the four GHG emissions. The carbon footprint of pork was intermediate between those of cattle and poultry products [26, 36]. However, in 2001 two thirds of Canada's livestock GHG emissions came from the western Canadian beef industry [37].

Dyer and Desjardins [38] compared protein-based GHG emission intensities from five international reviews [39–43] of beef, pork, and chicken. The emission rates for intensively produced beef were roughly three to four times higher than that of pork, and the GHG emission intensity of chicken was slightly more than half that of pork. In spite of the ranges associated with each of these other sources, these inter-livestock type comparisons were similar to the livestock differences reported by Dyer and Desjardins [44]. The GHG emissions difference between beef and pork was reaffirmed by Vergé et al. [37], who used a soil carbon payback approach to link the respective LCC land use with soil carbon. The payback period, however, is a qualitative and abstract concept that does not use the same dimensions to equate SOC to other terms in GHG emission budget calculations. Nevertheless, the payback period illustrates that SOC is a carbon sink and not necessarily a CO_2 emission term.

Many previous livestock-GHG analyses were not useful for the comparison of livestock types because the GHG emission intensities of these industries were not all based on the same production unit [38]. As the only common denominator to all livestock food commodities, animal quality protein is the best measure of the food value gained from livestock [26]. The GHG-protein ratio [38] also equated the carbon footprint of livestock products to the animal quality protein that can be derived from edible pulses [28]. Pulse proteins could dramatically reduce GHG emissions [7, 8, 28]. But for a society accustomed to red meat as their main protein source, a significant consumer shift towards plant proteins is unlikely in the near future.

More recently, a tri-variable scenario analysis was undertaken in Canada of the carbon footprint of Canadian carcass production [19, 25, 38, 44]. The three scenarios included (1) reducing the intake of red meat for the health benefits of Canadians, (2) the balance between the weights of domestic beef and pork coming into the Canadian food market and (3) the balance between feed grains and perennial forage in the diet of beef cattle. The scope was limited to the supply of animal quality protein to Canadian consumers and it was assumed that broiler production could be increased to maintain a fixed supply of protein to Canadian consumers. While these scenarios yielded many valuable insights about the carbon footprint of the Canadian livestock industry, the complexity of this interacting set of scenarios made it difficult to extract clear policy options or guidance to consumers. More importantly, it was difficult to determine the implications for Land Use Change (LUC) and the role of SOC [16] in livestock carbon footprints.

In a later stage of this scenario analysis, Dyer and Desjardins [44] equated beef GHG emissions to SOC when comparing four beef-pork scenarios. But these scenarios all involved beef-pork-broiler combinations rather than the two red meat animals: beef and pork. While it quantified the land uses for each scenario, it failed to link these land uses directly to the two main types of livestock. From a policy perspective, this analysis required each of the four scenarios to be deciphered into the optimum pig and beef cow populations. Regardless, Dyer and Desjardins [44] concluded that the carbon footprint of pork is lower than that of beef.

A follow-up video slideshow highlighted the combined carbon sequestration-rewilding opportunity that a LUC from beef to pork would offer [45]. Nevertheless, the complexity of the previous tri-variable scenario analysis suggests that, in order to realize the changes in the policy and consumer preferences needed to bring about meaningful GHG reductions, the focus should shift to just the beef-pork differences. Moreover, the carbon footprint advantage of pork over beef should be translated into a more convincing argument for policymakers and consumers. The success of that argument will depend on how robust the beef/pork GHG ratio is over time and how much farmland is involved.

2.2. Historical Perspective on Pigs and Cattle

A consumer shift from beef to pork must also overcome the reluctance of consumers to eat pork. Although less obvious than the carbon footprint, modern consumer trends can be influenced by biblical texts and historic social values, either subliminally or by faith. However, these factors are not quantifiable, and their origins had to be extracted from early human history. This extraction process relied on several informal sources, including video documentaries, to determine whether the historical reasons for the beef over pork preference are still valid today.

2.2.1. Cattle

Taurine cattle, including most European and North American breeds, were domesticated in the Near East from wild aurochs about 10.5 thousand years ago [46, 47]. The traditional benefits of cattle to humans include meat, milk and as draught animals [48]. The global spread of cattle herding, as with all forms of pastoralism, stems from the ability of ruminants to convert grassland (cellulose) into human food [49, 50]. This ability to exploit a perennial ground cover avoids periods of bare soil which allow SOC to be lost [29]. Soil cover is the justification for grazing cattle to maintain and sequester soil carbon as a way to mitigate agricultural GHG emissions [15, 37].

A case for the potential role of grazing beef cattle in restoring grassland SOC was promoted in a documentary video, "Guardians of the Grasslands" [51]. However, too much focus on grazing can draw attention away from two aspects of beef production. Over-stocking can compromise the ecological benefits of grazing [52, 53]. In the Canadian beef industry the grass-fed cattle from ranches are fattened for market in high-density feedlots on high energy feed grains [31]. Plus, the breeding cows not being finished for market need supplemental winter feed [54]. Hence, rangeland grazing is only one stage in the life cycle of beef. Also, at one calf per year, cattle reproduction is an inefficient protein source compared to pigs and chickens [26].

2.2.2. Pigs

Domestic pigs include two major forms; one from Europe (Sus scrofa) and one from Asia (Sus indicus) [55]. Pigs were domesticated in the Near East over 10 thousand years ago and introduced to Europe 6.5 thousand years ago [56]. In spite of the Near Eastern pigs coming into Europe [57], the European pig is more closely related to European wild boar than to the Near East pigs [56–58]. This is believed to be because early pigs that were allowed to forage unfenced interbred with wild boars [59]. The pigs domesticated in China 10 thousand years ago do not have the same wild boar influence [60].

Pigs digest their food differently than cattle and other ruminants [61]. Because they are monogastric (only one stomach chamber), they cannot use enteric bacteria to convert cellulose into food energy [62]. Therefore as non-ruminants, their diet depends on grains, pulses and other foods that could potentially feed humans [63]. Unlike cattle, one healthy sow can give birth to 10 new pigs with just a four month gestation period [55]. Consequently, a sow can produce more than 20 pigs per year [32]. However, feral pigs can pose several health and environmental risks (heightened by their wild boar ancestry), including rooting up both crops and wild plant communities, and eating carrion or other parasite-carrying materials [63]. Additionally, their high fecundity means that feral pig populations can and do become uncontrollable [64, 65]. Unlike ruminants, therefore, pigs are unsuitable for free-range husbandry and play no role in pastoralism [66].

2.2.3. Social and Consumer Preferences

From July 2023 to June 2024, the average Canadian price of slaughter calves was two to three times higher than marketable pigs on a per-unit-of-live-weight basis [67]. This price difference reflects the difference in social status between pork and beef. Pork production is also concentrated in a very small number of farms compared to beef feedlots [68], which can intensify manure handling problems and nitrate leaching into groundwater, and cause local complaints about the bad smell. Pork has a stigma of being unclean and a source of disease, including (among others) Trichinosis and swine flu [63]. Several major religions (the best known being Judaism) require that meat only come from animals that chew their cud [50]; meaning ruminants. This religious taboo did not start with Judaism [65]. There was a gradual decline in the popularity of pork that started in the Bronze Age when Middle Eastern people began to urbanize [65]. Even in Israel there were regional differences in pork consumption patterns [66], which casts further doubt on the biblical origin of the pork taboo. The lower social status of pork, however, was not a factor in China [60].

With modern pig farms, the pork taboo is no longer justified [50, 69]. In confined housing, where the pig diets are limited to feed crops (and occasionally table scraps), Trichinosis is not a significant risk [70], and the parasite risk is eliminated with proper cooking [71]. Although the fear of Trichinosis is often seen as biblical wisdom, this link was only found in the 19th Century, long after the origin of the pork taboo [50]. Pigs do not transfer swine flu to people; the converse is reportedly far more likely [72]. In contrast, Anthrax, which cattle carry, does not attract the same public attention [50]. Some pig behavior patterns, such as eating filth and wallowing in mud and excrement (a heat-coping behavior since pigs do not sweat), are only seen when pigs are concentrated in unregulated and squalid city environments [50]. Neither behavior is seen when pigs are given enough space and proper manure management [73]. Since the health of pigs on the farm directly translates into enhanced production [74], modern pork producers have an incentive to ensure that their pigs are kept clean and healthy.

The pork taboo only partly explains the lower socioeconomic status. Because pigs reproduce quickly and require little or no land [26], pigs became associated with the poor and landless [50, 65]. Unlike the larger domesticated animals, pigs provided no wealth-generating by-products, such as leather, wool or draft power, leaving the rich little economic motivation for owning them [74]. Although the smaller and more efficient chickens could out-compete pigs as a household-based protein source [75], pigs retained a place in Europe as the commoners' meat [50, 65].

3. Materials and Method

3.1. The GHG Emissions Model

This analysis used a purpose-built model based on the Unified Livestock Industry and Crop Emissions Estimation System (ULICEES). This model calculates the emissions of CH_4, N_2O, and fossil CO_2 from livestock production in Canada [37]. ULICEES was an assemblage of individual GHG emission studies of the four dominant livestock industries in Canada, that is dairy, beef, pork and poultry [30, 33], as well as sheep [34].

ULICEES has been successfully applied to a wide range of land use and animal husbandry issues because it included detailed information on life cycles and livestock feed [76]. However, sources for the required life cycle data were limited to agricultural census records which have not been gathered since 2001, and livestock diet data which were only available from one survey [77, 78]. These limitations restricted ULICEES application to 2001 [37] and partially to 2006 [76]. To overcome this temporal restriction, two slightly different ULICEES meta-models were created. Both meta-models indexed the two sets of census year results to the breeding female population of each livestock type for other years using the more commonly available annual livestock survey data [79]. In the first meta-model, Dyer et al. [76] indexed the ULICEES output to the other years. In the second meta-model, Dyer et al. [25] indexed the previously published livestock GHG emission budget estimates from Vergé et al. [30–34] for 2006 to the other years.

The earlier meta-model from Dyer et al. [76] was adapted for this analysis since it incorporated some upgrades to the original ULICEES model. Compared to the type-specific GHG emission estimates [31, 32] referenced by Dyer et al. [19], the GHG emission estimates from this analysis underestimated the GHG emissions from beef and over-estimated the GHG emissions from pork for 2001; resulting in a small narrowing of the beef-pork GHG emission difference. All versions of ULICEES recognize livestock as major sources of CH_4, N_2O and fossil CO_2. Manure storage is an important source of CH_4 from all livestock types. Methane is a critical term for comparing livestock GHG emission budgets because enteric CH_4 is only emitted by ruminants. Manure storage and chemical fertilizer are both sources of N_2O emissions. Fossil CO_2 emission estimates were derived from a sub-model for both on- and off-farm energy use [80–83].

SOC, a critically important addition to this ULICEES meta-model, was expressed on an annual basis as 2.1 tCO_2 ha^{-1} over 20 years [16, 44]. Soil is a carbon sink when land is converted from annual crops to perennial forage, whereas LUC from perennial to annual soil cover makes SOC a source of CO_2. SOC is a term in the beef GHG emission budget but not the pork GHG budget. Hence, SOC change (Δ) and enteric methane are the distinguishing differences between the beef and pork GHG emission calculations.

The CO_2 equivalent (CO_2e) emissions budget for beef is:

$$CO_2e_{\text{ beef}} = CH_{4\text{ manure}} + CH_{4\text{ enteric}} + N_2O_{\text{ manure}} + N_2O_{\text{ fertilizer}} + CO_{2\text{ fossil}} - \Delta_{\text{year}}SOC \quad (1)$$

The CO_2e emissions budget for pork is:

$$CO_2e_{\text{ pork}} = CH_{4\text{ manure}} + N_2O_{\text{ manure}} + N_2O_{\text{ fertilizer}} + CO_{2\text{ fossil}} \quad (2)$$

The CO_2e GWP factors used in this analysis were 25 times that of CO_2 for CH_4 and 298 times that of CO_2 for N_2O over 100 years [84]. The GHG emissions budgets described by Equations (1) and (2) also describe the GHG emissions budgets that were calculated in the original ULICEES model [37].

Except for enteric methane, all other terms in the two GHG emissions budgets (Equations (1) and (2)) depend on the land base that supports the livestock production. Vergé et al. [30] defined the land base needed to support dairy cows as the Dairy Crop Complex. This concept was later broadened into the LCC that was used in all of the subsequent Canadian livestock GHG emissions budget models referenced in this paper[35, 37]. For each livestock type (l), the basic LCC Area (A) calculation from Population (P), diet (V) and the Yield (Y) of each feed crop (c) in ULICEES is as follows:

$$A_{l,c} = P_l \times V_{l,c}/Y_c \quad (3)$$

With livestock diet data only available from one year[77, 78], the meta-model was not sensitive to temporal shifts in diet. All crop yields were indexed to their respective 2001 quantities from annual crop survey data. This meant that the dynamic drivers of Equation (3) were crop yields and population. Although not directly connected to Equation (3), changing tillage practices have caused a trend in the fossil CO_2 emissions from farm field work[80]. As well, a dramatic increase in nitrogen fertilizer use in Canada[85] has been driving increased N_2O emissions and the indirect energy use for nitrogen fertilizer manufacture and supply. Furthermore, the rates of fertilizer increase are crop-specific[86], is an important factor in differentiating the GHG emission rates from pork and beef over time.

3.2. Comparing Beef and Pork Carbon Footprints

The input terms required for the beef-pork carbon footprint comparison (**Table 1**) were generated by the ULICEES meta-model. The years of inputs listed in **Table 1** represent the seven census years from the 1990–2022 time series generated by the meta-model. The areas in **Table 1** are the crop complexes for beef and pork production (Equation (3)), for which the beef crop complex has been disaggregated into feed grains and harvestable perennial forage. The GHG emissions from beef and pork were generated from Equations (1) and (2), respectively. Dyer et al.[26, 76] calculated protein as a fraction of the live weight of market animals for 2001. The meta-model indexed this 2001 protein estimate to other years by the year to 2001 breeding female population ratios. The two protein quantities shown in **Table 1** for 2001 were taken from Dyer et al.[26, 76].

3.3. Comparing 2001 and 2021

Figures 1 and **2** compare the land use and carbon footprints of beef and pork for 2001 and 2021, respectively. These two figures consist of two indicators that use protein production per year as the common denominator. Since both indicators are based on intensities, rather than total impact, they are both expressed as *per ton of protein* (ptp). For simplicity only two land uses are considered: feed grains and harvestable hay. As was done by Dyer et al.[19, 25], both figures treated Canada as one agricultural region.

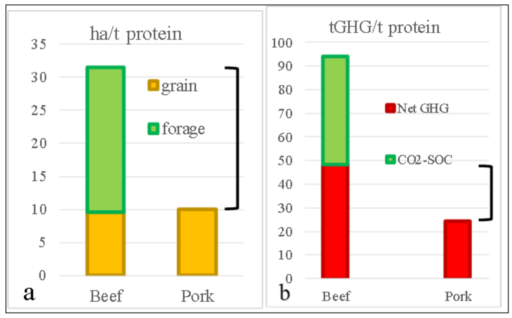

Figure 1. Comparison of the (**a**) required areas and (**b**) GHG emissions in the Canadian beef and pork industries on a unit of protein basis for 2001.

The indicator used in **Figures 1a** and **2a** is ha of cropland ptp. Permanent pasture land was excluded from this comparison because that land is not usable for annual feed grains[87], and would not normally be cultivated. Since the pig diet only includes grain (no roughage), the land in permanent pasture (most of which is considered rangeland in Canada) is not interchangeable with the pork crop complex. The areas of perennial forage for beef in **Figures 1a** and **2a** are shown in green. The areas in feed grain for both beef and pork are both shown in gold, with the bar showing the total area supporting beef cattle having both a gold and a green portion for grain and forage, respectively.

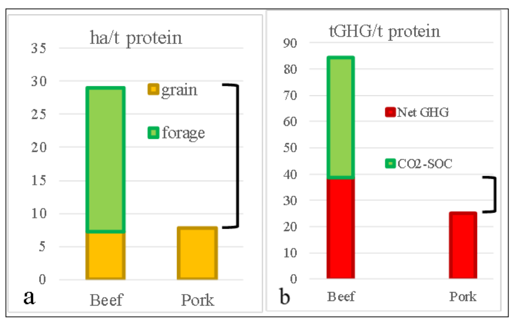

Figure 2. Comparison of the (**a**) required areas and (**b**) GHG emissions in the Canadian beef and pork industries on a unit of protein basis for 2021.

Figures 1b and **2b** compared the respective annual tCO_2e emissions ptp for these two livestock types. The

Table 1. GHG emissions and protein production from the Canadian beef and pork industries, and the areas that support those two industries during the census years from 1991 to 2021.

	Beef				Pork		
	GHG	**Protein**	**Grain**	**Forage**	**GHG**	**Protein**	**Grain**
Years	**MtCO2e**	**Mt**	**Mha**	**Mha**	**MtCO2e**	**Mt**	**Mha**
1991	21.5	0.20	1.8	4.3	5.5	0.21	2.0
1996	27.1	0.25	2.1	5.3	5.7	0.22	2.0
2001	28.6	0.25	2.4	5.6	7.4	0.28	2.8
2006	30.7	0.28	2.2	6.3	7.2	0.31	2.8
2011	24.4	0.22	1.7	4.8	5.9	0.23	2.2
2016	20.7	0.21	1.4	4.6	6.3	0.24	1.8
2021	21.0	0.21	1.5	4.67	6.9	0.25	2.0
Average	24.9	0.23	1.9	5.1	6.4	0.25	2.2

weight of GHG emissions for pork is shown in red, whereas the total weight of GHG emissions from beef is shown red and green. The red portion of the beef GHG emission bars in **Figures 1b** and **2b** represent the remaining GHG emissions after an allowance for carbon sequestration. They are, therefore, the Net GHG emission weights from beef cattle. The soil carbon stored in the land planted to perennial forage is credited to the beef industry to offset GHG emissions from that industry. The sequestered carbon, expressed as CO_2 per year, and designated as CO2-SOC, is shown in green.

The left-facing brackets in **Figures 1** and **2** show the meaningful differences between pig and beef cattle production. These brackets represent the possible reductions in area and GHG emissions ptp for a complete (hypothetical) replacement of beef production with pork production in Canada. For **Figures 1a** and **2a**, the meaningful differences are between the total area for beef and the grain growing area for pork. The bracketed areas in **Figures 1a** and **2a** are both in the green portions of the beef area bars. The beef (*bf*) to pork (*pk*) difference (Δ) in area ptp was calculated as:

$$\Delta \text{ Area/Protein} = ((\text{Area}_{\text{grain},bf} + \text{Area}_{\text{forage}})/\text{Protein}_{bf}) - (\text{Area}_{pk}/\text{Protein}_{pk}) \quad (4)$$

The left-bracketed differences in **Figures 1b** and **2b** are between the Net GHG emissions from beef and the pork GHG emissions (both in red). However, the actual calculation of the bracketed GHG emissions is more accurately illustrated by including the calculation of the Net beef GHG from All beef (*all bf*) and forage. The beef to pork difference in GHG emissions ptp was calculated as:

$$\Delta \text{ GHG/Protein} = ((\text{GHG}_{allbf} - \text{GHG}_{\text{forage}})/\text{Protein}_{bf}) - (\text{GHG}_{pk}/\text{Protein}_{pk}) \quad (5)$$

The analysis presented by **Figures 1** and **2** was extended to all seven of the census years shown in **Table 1**. This temporal extension of the beef-pork carbon footprint comparison to other census years (**Table 2**) will reveal any trends in the terms used in **Figures 1** and **2** and assess the robustness of the findings in those two figures.

4. Results

4.1. GHG Emissions Model Output

In **Table 1** there were very little year to year variations in any of the columns. The relative standard deviations over seven years ranged from 12% to 20%. The term with the greatest beef to pork difference was GHG emissions. The average total GHG emissions from beef (not including SOC) was 4.1 times the average GHG emissions from pork. The two highest deviations were for the two grain areas (beef and pork). On average the beef grain areas were 16% lower than the pork areas, and the pork area exceeded beef grain area in all years. The average ratio of forage to grain areas supporting the beef industry was 2.7. On average the amount of pork protein was 7% higher than the beef protein, but the beef industry produced less protein than pork in all years.

Figure 3 shows the respective breeding populations for beef and pork, the main driver of the meta-model. For consistency with other applications of this meta-model, the data for the selected census years were taken from annual survey records [88, 89]. But since the survey records for pigs did not start until 2008, sow populations for 1991, 1996, 2001 and 2006 were taken from census records [32, 90]. The two populations have very similar distribution shapes over time, although on average beef cows outnumber sows by over three to one. Both populations peaked in 2006 before stabilizing in 2016 and 2021. The typical live weight of beef cows is roughly 2.5 times the typical live weight of sows[91]. In 2021, even though smaller, 1.2 million sows produced 0.25 Mt of protein, while 3.7 million beef cows only produced 0.23 Mt of protein (**Table 1**).

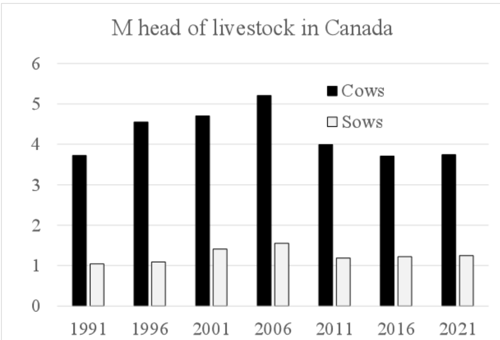

Figure 3. Breeding female populations for pigs (Sows) and beef cattle (Cows) for seven census years in Canada.

4.2. Protein-Based Intensity of Land Use and GHG Emissions

For 2001, **Figure 1a** shows that the grain area for beef (gold) was slightly less than half as much as the area of harvested forage (green). It also shows that pork required only a little more area of feed grain than beef for the same amount of protein. The bracketed area in 2001 was 21 ha ptp. **Figure 1b** shows that in 2001 the beef area credited with carbon sequestration (CO2-SOC) accounted for only half of the total CO_2e emission intensity of Canadian beef. The Net CO_2e ptp (after subtracting CO2-SOC from beef GHG emission intensity) was two and a half times the GHG emission intensity of pork. The bracketed emission difference in **Figure 1b** was 40 tCO_2 ptp, representing a two thirds reduction from the Net GHG emissions ptp produced by Canadian beef cattle after subtracting CO2-SOC. The pork GHG ptp (red) was 23.3% of the beef GHG ptp before subtracting CO2-SOC. The total beef (red and green) and pork (red) GHG emissions for 2001 (**Figure 1b**) were very close to the 2001 results for these two livestock types from Dyer et al.[26].

By 2021, the areas for both grain terms in **Figure 2a** had decreased from 2001, whereas the area for forage did not change. The difference in grain areas increased, with the area for pork 9% higher than for the beef grain area (gold). The grain area for beef (gold) was only a third as much as the area of harvested forage (green). The bracketed area in 2021 remained at 21 ha ptp. The Net GHG emission intensity from beef was 6 $MtCO_2$e ptp higher in **Figure 2b** than in **Figure 1b**. But the GHG emission intensity was unchanged for CO2-SOC and decreased very little for pork in **Figure 2b**. Consequently, the contribution of carbon sequestration to the beef GHG emission intensity showed no change between 2001 and 2021, whereas the Net CO_2e rose to almost three times the GHG emission intensity of pork. The bracketed emission difference increased from 40 tCO_2 ptp in 2001 to 47 tCO_2 ptp in 2021, and represented a 65% reduction in the Net GHG emissions from the 2021 Canadian beef cattle, whereas the pork GHG ptp was 22% of beef GHG ptp before subtracting CO2-SOC.

4.3. Meta-Model Assessment over Seven Census Years

To extend the intensity based analysis used in **Figures 1** and **2** to all seven years, all results in **Table 2** were expressed as ptp per year. The terms of the extended analysis shown in **Table 2** are the same as those used in **Figures 1** and **2**. Although the weights of pork protein and beef protein shown in **Table 1** were slightly different, because the analysis was based on intensity indicators, the area and GHG emission results shown for these two livestock types in **Table 2** were dimensionally compatible.

The average total land use by the Canadian beef industry was 30 ha ptp, whereas the average land use for Canadian pork production was only 9 ha ptp, leaving the average beef-pork area difference (left-bracketed in **Figures 1a** and **2a**) at 21 ha ptp. The average Net beef GHG emissions minus the average pork GHG emissions (left-bracketed in **Figures 1b** and **2b**) was 41 tCO_2e ptp. The average Net beef GHG emission intensity, after subtracting 46 tCO_2 ptp (for CO_2-SOC), was 86 tCO_2e ptp.

On average, beef production required just over a third as much (37%) area for grain as it did for harvestable forage, and the average beef grain area was 90% as much as the area required by the pork industry. The average pork grain area was 30% of the average of all areas (grain plus forage) required for beef. Pork GHG emission intensities were on average 38% of Net beef GHG and 23% of beef GHG before subtracting CO2-SOC. The difference in GHG emission

Table 2. Areas in Canada that supported Canadian beef and pork production, the GHG emissions from these two livestock production systems, and the area and GHG emission differences between beef and pork. All terms are shown on a unit of protein basis for census years from 1991 to 2021.

	Area (Sub-Figures a)			**GHG (Sub-Figures b)**			**Δ Area**		**Δ GHG**	
	ha/t protein			**tCO_2/t protein**		**ha/t protein**			**tCO_2/t protein**	
	Beef Grain	**Forage**	**Pork Grain**	**Net Beef**	**CO_2-SOC**	**Pork**	***All Beef*[1]**	**Pork**	**All Beef**	***Net Beef*[1]**
Year	***gold*[2]**	***green*[2]**	***gold*[2]**	***red*[2]**	***green*[2]**	***red*[2]**	***- pork***	**- beef grain**	**- pork**	***- pork***
1991	9	21	10	42	45	25	21	1	62	17
1996	8	22	9	45	45	24	21	1	66	21
2001	10	22	10	48	46	24	21	0	70	24
2006	8	22	9	45	47	22	21	1	70	24
2011	8	22	9	48	47	23	21	2	72	25
2016	6	22	8	37	45	24	21	1	59	14
2021	7	22	8	39	46	25	21	1	59	13

1, The two difference terms in italics reflect the left-bracketed portions of the barcharts of **Figures 1** and **2**.
2, The colours (in italics) reflect the corresponding terms shown in the barcharts of **Figures 1** and **2**.

intensity between the Net beef and pork (left-bracketed in **Figures 1b** and **2b** was 62% of the average Net beef GHG emission intensity.

Although some modest trends were noted in **Table 1**, **Table 2** shows that the year to year differences were small compared to the differences among the columns. This stationarity reflects the small number of temporal inputs available to drive the meta-model, particularly the limited data on livestock diets. The beef grain and pork areas had very slight downward trends, and beef forage areas had no trend. This was because for harvested perennial forage the crop complex calculation was overridden by the area statistics, which slightly favours the beef industry. The pork GHG emissions ptp were less than half the Net GHG emissions ptp from beef in all seven census years. The small, but consistent, difference in area required by pork over the beef grain area was never enough to nullify more than a small fraction of the land in forage, leaving a large CO2-SOC term in **Figures 1b** and **2b**.

To determine a theoretical maximum mitigation potential, a scenario involving a conversion from beef production (excluding grass fed-beef) to pork production was assumed for 2021. The outcomes of this test depended on how the residual 4.5 Mha of forage land made free by the theoretical beef to pork shift in 2021 (the bracketed area in **Figure 2a**) would be used. Two different quantities of GHG emissions can be mitigated, depending on whether or not the freed land was re-cultivated. These two 2021 GHG emission quantities were estimated by multiplying the 2021 estimates from the two Δ GHG columns in **Table 2** by the 2021 beef protein weight in **Table 1**. If that area was re-cultivated for annual crops (beef protein × (GHG*Net beef – pork*)), then only 10.0 $MtCO_2e$ could be mitigated per year. If that area was left under a perennial ground cover (beef protein × (GHG*All beef – pork*)), then 19.8 $MtCO_2e$ could be mitigated per year, equivalent to 23% of the GHG emissions budget of Canadian agriculture [20]. But even the 10.0 $MtCO_2e$ is 60% greater than the 2021 carbon footprint of the Canadian pork industry (**Table 1**), and equivalent to 12% of the sector's GHG emissions budget [20].

5. Discussion

The two columns in **Table 2** (headings in italics) that correspond to the left bracketed terms in **Figures 1** and **2** provide the most important validation of the two figures. The limited temporal variations in **Table 2** indicate that the calculations presented in **Figures 1** and **2** were consistent over time. These figures revealed that, even when beef is credited with the carbon sequestration under hay, pork consistently emitted much less GHG for an equivalent weight of protein than did beef. Although the pork grain area always exceeded the beef grain area in **Table 2**, the land used by pork always left most of the land that would be used to grow perennial forage free for another use if beef production ceased.

The slight increase in the carbon footprint advantage of pork over beef from **Figure 1b** to **Figure 2b** and the modest upward trend in beef GHG emission intensity (**Table 2**) is consistent with the general increase in nitrogen fertilizer sales in Canada between 2001 and 2021 (Statistics Canada, 2023). Between 2001 and 2021 increases in the nitrogen fertilizer application rates on the two main feed grains, Barley and Grain corn, were much less than the rates of increase for Spring wheat and Canola [86], two of Canada's main commercial export crops. Whereas nitrogen application rates for Barley, the main beef (and western) feed grain [32], increased modestly, nitrogen fertilizer use on Grain corn, the main pork (and eastern) feed grain [31], showed almost no increase between 2001 and 2021 [86]. Consequently, the carbon footprint of pigs got almost no upward pressure from nitrogen fertilizer, while beef GHG emissions, accounted for the increased difference between **Figure 1b** and **2b**.

The test for a complete 2021 conversion from beef to pork production generated two very different potential GHG mitigation amounts, depending on whether the land freed by the conversion was cultivated or left under perennial foliage. But the newly freed land can create a number of downstream impacts and benefits, depending on the chosen land use. Quantifying the carbon footprints of these new land uses would depend on the crops grown, and/or the mix of livestock to be supported by the feed produced. However, the use of this freed land did not involve any beef-pork interactions that would impact the findings from **Figure 2** or **Table 2**. Since these hypothetical options were outside the goal of this analysis, no estimates of the range of their GHG emission budgets are provided. Nevertheless, they warrant a qualitative discussion. The four options for using the 4.5 Mha of freed land include:

(a) continuing to grow perennial forage to raise additional grass-fed beef,

(b) growing more feed grains to raise other livestock,

(c) growing edible crops such as pulses or wheat,

(d) rewilding to restore biodiversity and natural habitat.

Options a and b would produce additional protein over the new protein coming from the expanded pork production. Earlier results from ULICEES-based assessments indicate that using that land for feed grains (Option b) would give lower GHG emissions than using it for forage for grass-fed cattle (Option a), particularly if those grains were fed to non-ruminants [19, 76]. Ideally, the additional protein from Options a and b would offset the need to produce the same amount of protein somewhere else, whereas Option c would offset the need to produce the same edible crops somewhere else. Option c will have greater importance when Canada is called upon to assist international food aid programs driven by climate change-related famines or disasters [92]. Ignoring the enteric methane from the grass-fed cattle, Options b and c would have higher carbon footprints due to the additional N fertilizer [86] and field operations [81] required by annual crops.

Options a and d would both benefit SOC, but Option d would sacrifice additional meat production for increased biodiversity, particularly if regenerative grazing was implemented [93]. Option d could go further by rewilding with native ungulates [94]. However, returning areas of tame pasture or hay to native grassland habitat involves significant ecological challenges to achieve the same biodiversity benefits as undisturbed rangeland [51]. Nevertheless, many developed nations do not have the vast areas of undisturbed rangeland still viable in Canada. For those nations, Option d could be a welcome opportunity to recreate their own grassland habitat.

None of the calculations in this analysis involved rangeland. Instead, it was treated as a constant term since carbon sequestration is driven by LUC, rather than by land uses that are unlikely to change. Rangeland, therefore is less important for sequestering carbon than for keeping SOC from being lost. This SOC stability requires regulated stocking rates on rangeland [52, 53]. But Canada's rangeland is a natural ecosystem that must be protected, along with its biodiversity and SOC [51]. If rangeland cattle are marketed as grass-fed beef [44], there is still a role for rangeland to play in the Canadian livestock industry. However, grass-fed beef lacks the tenderness that most consumers want, and these cattle take longer to grow, which lowers marketable carcass weight yields and raises the price for consumers [95]. Growing more slowly on the high roughage diet, grass-fed beef have to be kept alive longer, thus emitting more enteric methane over their lives.

The need for winter feed for grass-fed cattle in Canada [54] comes at a time when most Prairie rangeland is dormant. ULICEES includes the winter feed needed for the breeding rangeland cattle as a part of the crop complex of the whole beef industry [37]. For example, the diet of replacement heifers quantified by ULICEES [31, 37] provided a winter feed proxy for grass-fed, rangeland cattle [19]. But with these cattle decoupled from the beef crop complex, the additional feed would have to be harvested elsewhere, and hence, grass-fed beef production on rangeland is not a closed system. Since this analysis did not include rangeland cattle, sourcing winter feed for these grass-fed cattle was beyond the scope of this analysis.

The left-bracketed GHG emissions in **Figure 2b** integrated over beef protein, as in the above beef-pork conversion scenario, represent a potential reduction of 10.0 $MtCO_2e$. Just two-thirds of this reduction could nullify the 6.3 $MtCO_2e$ (**Table 1**) from the Canadian pork industry in 2021, eliminating the carbon footprint of the protein provided by that industry. The left-bracketed GHG emissions in **Figures 1b** and **2b** are the result of both fecundity and enteric methane from ruminants. Fecundity, the effective reproductive rates [26], clearly favour pigs over beef cattle. This higher reproductive efficiency was demonstrated in **Figure 3**, where the much smaller population of sows could produce as much protein as the beef industry, with no significant enteric methane emissions.

The underpinning assumption of this analysis was that livestock production systems can be compared on the basis of protein equivalence. For just comparing mammalian carcass products, using live weights as a proxy for protein would lead to conclusions very similar to this analysis [44]. But the wider applicability of the GHG-protein ratio [38] makes it a better indicator for comparing the carbon footprints of carcass and non-carcass livestock products, as well as pulse proteins. Nevertheless, this assumption treats protein supply as a closed system [25]. In most developed nations, affluent consumers eat red meat for pleasure as much as to maintain their protein requirement [19]. However, such overconsumption ignores planetary boundaries [1–6]. Agriculture and food policies must embrace an upper limit on animal protein consumption for both human health and the planet [7, 8, 25]. Fecundity and feed efficiency also explain why less land is needed to raise pigs than beef cattle. The hay needed by cattle requires much more land than does the grain needed for pig feed, partly because much of that hay is required to maintain the breeding cows. In addition to the hay they consume, feedlot-finished beef cattle require almost as much feed grain as pigs for the same protein production.

6. Conclusions

Using the paired area-GHG emission bar charts to define the carbon footprint differences between the beef and pork industries provides a convincing argument for supporting the Canadian pork industry. This was achieved by bringing together LUC, SOC and the respective annual GHG emission budgets of beef and pork into one composite graphic illustration. The link between the two area sub-figures and the two GHG emission sub-figures required the LCC. This message is strengthened by the consistently lower carbon footprint of pork production over the three decades (**Table 2**). Some caution is warranted with these results since only one livestock diet survey was available. For more precise future LCC calculations, another Canada-wide livestock diet survey should be undertaken. With the appropriate land use decisions, pig farms have a role to play in sequestering carbon, although not as direct as the role that beef production plays. Moreover, this analysis demonstrates the weakness of policy decisions that lump beef and pork together as red meat.

The analysis drew two important conclusions about the carbon-sequestering role of pigs. First, when the potential carbon sequestration in the land growing harvestable forage is credited to the beef industry, that CO_2e emissions offset does not reduce the carbon footprint of beef enough to match the lower carbon footprint of pork. The first conclusion was not new, but it corroborates the same conclusion reached by Dyer and Desjardins [44] and verified its long term persistence. The second conclusion was that most of the land required to grow hay and tame pasture for beef is not needed to feed the protein-equivalent pig population, which reduced the impact of SOC as a CO_2e emissions offset. The second conclusion required a direct beef-pork comparison which the multi-species scenarios used by Dyer and Desjardins [44] could not provide. The beef to pork conversion scenario suggests that how the freed up land is used could have as high a carbon footprint impact as the initial GHG emission reductions.

The conclusions from this analysis do not apply to rangeland cattle sold directly as grass-fed beef; a use of marginal land that, if properly managed, could be sustainable [44], the winter feed requirement notwithstanding. Therefore, for the consumer, an overall move from beef to pork with the occasional consumption of grass-fed beef provides the red meat option with the lowest carbon footprint [45]. From a policy perspective, diverting feed grains to pigs and leaving cattle that can convert cellulose to protein to graze will lead to a lower carbon footprint for the Canadian livestock industry. For affluent Canadian consumers not ready to fully embrace plant proteins, or tired of chicken as their only meat option, this beef to pork transition is the easiest way to reduce their protein carbon footprint while still enjoying some red meat.

The carbon footprint advantage that pigs have over beef cattle suggests that creating incentives to encourage more pork production could be an effective livestock GHG mitigation policy. Consumer education of this carbon footprint advantage could be equally effective and would avoid the appearance of government favoring one group of producers over another. The 2021 beef industry promotion video, "Guardians of the Grasslands"[51], which portrays beef cows wandering over a pristine landscape, has accumulated over 100 thousand views. A similar promotion video is needed to show how effectively feeding grains to pigs instead of beef cows can reduce the carbon footprint of red meat consumption. Such promotion is unlikely to overcome consumer reluctance on its own, however, unless it also shows that the low social status and taboos of eating pork are historical artifacts that are no longer part of modern pork production[73]. But given the anecdotal nature of Section 2.2, a customer behavior analysis of Canadian meat consumers should accompany such promotion. This integrated message would help to motivate more consumers to choose pork over beef.

Author Contributions

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Institutional Review Board Statement

This study did not involve humans or animals, or require ethical review or approval.

Data Availability Statement

All of the data used to derive the results shown in the tables and graphs of this paper were extracted from agricultural census and survey archives maintained by Statistics Canada of the Government of Canada.

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There were no funding source or financial relationships that could have influenced the results presented. The Authors declare that there are no conflicts of interest.

References

[1] Abedi, M., 2018. Skip the Steak? Curb Meat Consumption to Combat Climate Change: Study. Available from: https://globalnews.ca/news/4537288/meat consumption-climate-change-study/ (cited 2 December 2024).

[2] Campbell, B.M., Beare, D.J., Bennett, E.M., et al., 2017. Agriculture production as a major driver of the Earth system exceeding planetary boundaries. Ecology and Society. 22(4), 8. Available from: https://www.ecologyandsociety.org/vol22/iss4/art8/

[3] Hood, M., 2020. G20 Carbon 'Food-Print' Highest in Meat-Loving Nations: Report. 16 July 2020. Report. Available from: https://phys.org/news/2020-07-g20-carbon-food-print-highest-meat-loving.html (cited 17 November 2024).

[4] Millstein, S., 2024. Why Eating Meat is Bad for the Environment and Climate Change, Explained. Available from: https://sentientmedia.org/why-is-eating-meat-bad-for-the-environment/ (cited 17 November 2024).

[5] Springmann, M., Clark, M., Mason-D'Croz, D., et al., 2018. Options for keeping the food system within environmental limits. Nature. 562, 519–525. DOI: https://doi.org/10.1038/s41586-018-0594-0

[6] Willett, W., Rockström, J., 2019. Healthy Diets from Sustainable Food Systems, Summary Report of the EAT-Lancet Commission. Available from: https://eatforum.org/content/uploads/2019/01/EAT-Lancet_Commission_Summary_Report.pdf (cited 2 December 2024).

[7] Goodland, R., 2014. A fresh look at livestock greenhouse gas emissions and mitigation potential in Europe. Global Change Biology. 20, 2042–2044. DOI: https://doi.org/10.1111/gcb.12454

[8] Mayerfeld, D., 2023. Our Carbon Hoofprint: The Complex Relationship between Meat and Climate. Print version: Springer International Publishing AG,c2023 ISBN 9783031090233. 233 pp. Available

from: https://www.amazon.ca/Our-Carbon-Hoofprint-Complex-Relationship/dp/3031090225 (cited 16 November 2024).

[9] Guterres, A., 2018. Secretary-General's Remarks at High-Level Event on Climate Change. United Nations. Available from: https://www.un.org/sg/en/content/sg/statement/2018-09-26/secretary-generals-remarks-high-level-event-climate-change-delivered (cited 16 November 2024).

[10] Charlebois, S., 2023. Food industry under the spotlight at COP28, 6 December 2023. Available from: https://troymedia.com/environment/food-industry-under-the-spotlight-at-cop28/ (cited 24 August 2024).

[11] Robinson, A., 2024. World Bank recipe for climate-friendly food systems: Cut meat subsidies. Corporate Knights. Summer. 23(3), 14. Available from: https://www.corporateknights.com/issues/2024-06-best-50-issue/ (cited 21 August 2024).

[12] Olsen, J.M., 2024. Gassy cows and pigs will face a carbon tax in Denmark, a world first. Available from: https://apnews.com/article/denmark-cow-tax-greenhouse-gases-9a570518639e0a1990806fd1a05ac11a (cited 10 November 2024).

[13] Garnett, T., 2009. Livestock-related greenhouse gas emissions: Impacts and options for policy makers. Environmental Science & Policy. 12, 491–503. DOI: https://doi.org/10.1016/j.envsci.2009.01.006

[14] Stehfest, E., Bouwman, L., van Vuuren, D.P., et al., 2009. Climate benefits of changing diet. Climatic Change. 95, 83–102. DOI: https://doi.org/10.1007/s10584-008-9534-6

[15] Liang, C., MacDonald, J.D., Desjardins, R.L., et al., 2020. Beef cattle production impacts soil organic carbon storage. Science of the Total Environment. 718, 137273. DOI: https://doi.org/10.1016/j.scitotenv.2020.137273

[16] VandenBygaart, A.J., McConkey, B.G., Angers, A.D., et al., 2008. Soil carbon change factors for the Canadian agriculture national greenhouse gas inventory. Canadian Journal of Soil Science. 88, 671–680.

[17] Wang,T., Kreuter, U., Davis, C., et al., 2024. Climate impacts of alternative beef production systems depend on the functional unit used: Weight or monetary value. PNAS. 121(31). DOI: https://doi.org/10.1073/pnas.2321245121

[18] Agriculture and Agri-food Canada (AAFC), 2021. Protein disappearance of animal protein sources in Canada. Available from: https://agriculture.canada.ca/en/sector/animal-industry/protein-disappearance-and-demand-species (cited 14 November 2024).

[19] Dyer, J.A., Desjardins, R.L., Worth, D.E., et al., 2020. Potential role for consumers to reduce Canadian agricultural GHG emissions by diversifying animal protein sources. Sustainability. 12(13), 5466. DOI: https://doi.org/10.3390/su12135466

[20] Desjardins, R.L., Worth, D.E., Dyer, J.A., et al., 2020. The carbon footprints of agricultural products in Canada. In: Mathu, S.S. (ed.). Carbon Footprints, Environmental Footprints and Eco-design of Products and Processes. The Crown: Ottawa, Canada. pp. 1–34. DOI: https://doi.org/10.1007/978-981-13-7916-1_1

[21] BBC News, 2021. Climate change: Do I need to stop eating meat?. Available from: https://www.bbc.com/news/explainers-59232599 (cited 2 December 2024).

[22] Mayer, A., 2019. Meat and the Environment: Do Canadians Know What's at Stake? What on Earth?. Available from: https://www.cbc.ca/news/technology/what-on-earthnewsletter-e-waste-elizabeth-may-1.5104341 (cited 2 December 2024).

[23] McMahon, J., 2019. Meat and Agriculture Are Worse for the Climate than Power Generation. Available from: https://www.forbes.com/sites/jeffmcmahon/2019/04/04/meatand-agriculture-are-worse-for-the-climate-than-dirty-energy-steven-chusays/ (cited 29 December 2024).

[24] He, D., Deng, X., Wang, X., et al., 2023. Livestock greenhouse gas emission and mitigation potential in China. Journal of Environmental Management. 348, 119494. DOI: https://doi.org/10.1016/j.jenvman.2023.119494

[25] Dyer, J.A., Worth, D.E., Vergé, X.P.C., et al., 2020. Impact of recommended red meat consumption in Canada on the carbon footprint of Canadian livestock production. Journal of Cleaner Production. 266, 121785. DOI: https://doi.org/10.1016/j.jclepro.2020.121785

[26] Dyer, J.A., Vergé, X.P.C., Desjardins, R.L., et al., 2010. The protein-based GHG emission intensity for livestock products in Canada. Journal of Sustainable Agriculture. 34(6), 618–629. DOI: https://doi.org/10.1080/10440046.2010.493376

[27] Nijdam, D., Rood, T., Westhoek, H., 2012. The price of protein: Review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes. Food Policy. 37, 760–770. DOI: https://doi.org/10.1016/j.foodpol.2012.08.002

[28] Dyer, J.A., Vergé, X.P., 2015. The role of Canadian agriculture in meeting increased global protein demand with low carbon emitting production. Agronomy. 5, 569–586.

[29] Abdalla, K., Mutema, M., Hill, T., 2020. Soil and organic carbon losses from varying land uses: A global meta-analysis. Geographical Research. 58(2), 167–185. DOI: https://doi.org/10.1111/1745-5871.12389

[30] Vergé, X.P.C., Dyer, J.A., Desjardins, R.L., et al., 2007. Greenhouse gas emissions from the Canadian dairy industry during 2001.

Agricultural Systems. 94(3), 683–693. DOI: https://doi.org/10.1016/j.agsy.2007.02.008

[31] Vergé, X.P.C., Dyer, J.A., Desjardins, R.L., et al., 2008. Greenhouse gas emissions from the Canadian beef industry. Agricultural Systems. 98(2), 126–134. DOI: https://doi.org/10.1016/j.agsy.2008.05.003

[32] Vergé, X.P.C., Dyer, J.A., Desjardins, R.L., et al., 2009. Greenhouse gas emissions from the Canadian pork industry. Livestock Science. 121, 92–101. DOI: https://doi.org/10.1016/j.livsci.2008.05.022

[33] Vergé, X.P.C., Dyer, J.A., Desjardins, R.L., et al., 2009b. Long Term trends in greenhouse gas emissions from the Canadian poultry industry. Journal of Applied Poultry Research. 18, 210–222. DOI: https://doi.org/10.3382/japr.2008-00091

[34] Dyer, J.A., Vergé, X.P.C., Desjardins, R.L., et al., 2014. A comparison of the greenhouse gas emissions from the sheep industry with beef production in Canada. Sustainable Agriculture Research. 3(3), 65–75. DOI: https://doi.org/10.5539/sar.v3n3p65

[35] Dyer, J.A., Vergé, X.P.C., Kulshreshtha, S.N., et al., 2011. Areas and greenhouse gas emissions from feed crops not used in Canadian livestock production in 2001. Journal of Sustainable Agriculture. 35(7), 780–803. DOI: https://doi.org/10.1080/10440046.2011.606493

[36] Scanes, C.G., Pierzchała-Koziec, K., 2024. Poultry and livestock production: Environmental impacts. In: Al-Marzooqi, A. (ed.). Modern Technology and Traditional Husbandry of Broiler Farming. InTech Open Access Publisher: Rijeka, Croatia. DOI: https://doi.org/10.5772/intechopen.1005641

[37] Vergé, X.P.C., Dyer, J.A., Worth, D.E., et al., 2012. A greenhouse gas and soil carbon model for estimating the carbon footprint of livestock production in Canada. Animals. 2, 437–454.

[38] Dyer, J.A., Desjardins, R.L., 2022. The GHG Protein Ratio: An indicator whose time has come. Highlights of Sustainability. 1, 105–112. DOI: https://doi.org/10.54175/hsustain1020008

[39] De Vries, M., de Boer, I.J.M., 2010. Comparing environmental impacts for livestock products: A review of life cycle assessments. Livestock Science. 128, 1–11. DOI: https://doi.org/10.1016/j.jclepro.2021.128799

[40] González, A.D., Frostell, B., Carlsson-Kanyama, A., 2011, Protein efficiency per unit energy and per unit greenhouse gas emissions: Potential contribution of diet choices to climate change mitigation. Food Policy. 36, 562–570. DOI: https://doi.org/10.1016/j.livsci.2009.11.007

[41] Nijdam, D., Rood, T., Westhoek, H., 2012. The price of protein: Review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes. Food Policy. 37, 760–770. DOI: https://doi.org/10.1016/j.foodpol.2012.08.002

[42] Vauterin, A., Steiner, B., Sillman, J., et al., 2021. The potential of insect protein to reduce food-based carbon footprints in Europe: The case of broiler meat production. Journal of Cleaner Production. 320, 128799. DOI: https://doi.org/10.1016/j.jclepro.2021.128799

[43] Poore, J.; Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science. 360 (6392), 987–992. DOI: https://doi.org/10.1126/science.aaq0216

[44] Dyer, J.A., Desjardins, R.L., 2021. Reconciling reduced red meat consumption in Canada with regenerative grazing: implications for GHG emissions, protein supply and land use. Atmosphere. 12(8), 945. DOI: https://doi.org/10.3390/atmos12080945

[45] Dyer, J., Desjardins, R., 2023. Using Protein as a Unifying Measurement of Livestock Carbon Footprints. Available from: https://www.youtube.com/watch?v=t0AxQwQQ3FE (cited 2 October 2024).

[46] McTavish, E.J., Decker, J.E., Schnabel, R.D., et al., 2013. New World cattle show ancestry from multiple independent domestication events. Proceedings of the National Academy of Sciences. 110(15), E1398–E1406. DOI: https://doi.org/10.1073/pnas.1303367110

[47] Scheu, A. Powell, A., Bollongino, R., et al., 2015. The genetic prehistory of domesticated cattle from their origin to the spread across Europe. BioMed Central Genomics 16, 54.

[48] Melletti, M., 2016. Cattle Domestication: from Aurochs to Cow. February 18, 2026. Available from: https://www.cambridgeblog.org/2016/02/cattle-domestication-from-aurochs-to-cow/ (cited 16 November 2024).

[49] Desjardins, R.L., Worth, D.E., Vergé, X.P.C., et al., 2012. Carbon footprint of beef cattle. Sustainability. 4, 3279–3301. DOI: https://doi.org/10.3390/su4123279

[50] Ragusea, A., 2020. Why billions of people won't eat pork (or why we don't know), October 26, 2020. Available from: https://www.youtube.com/watch?v=Sew4rctKghY (cited 16 November 2024)

[51] Wilson, B., Wray, S., 2021. Guardians of the Grasslands. Available from: https://www.youtube.com/watch?v=_CG4ROvCu0Y (cited 14 November 2024).

[52] Alemu, A.W., Janzen, H., Little, S., et al., 2017. Assessment of grazing management on farm greenhouse gas intensity of beef production systems in the Canadian Prairies using life cycle assessment. Agricultural Systems. 158, 1–13. DOI: https://doi.org/10.1016/j.agsy.2017.08.003.

[53] Lyons, R.K.; Machen, R.V., 2011. Stocking Rate: The Key Grazing Management Decision. Available from: https://edwards.agrilife.org/files/2011/03/2ll.pdf (cited 17 November 2024).

[54] Manitoba Agriculture, 2024. Winter Feeding and Shelter Requirements for Cattle. Available from: https://www.gov.mb.ca/agriculture/animal-health-and-welfare/animal-welfare/cattle-winter-feeding-and-shelter-requirements.html (cited 14 November 2024).
[55] Newman, M., 2019. Swine Domestication aka "The Pig Porkification Project", 4-H Animal Science Resource Blog, New Jersey Agricultural Experiment Station. Available from: https://4hanimalscience.rutgers.edu/2019/03/15/1747/ (cited 17 November 2024).
[56] Caliebe, A., Nebel, A., Makarewicz, C. et al., 2017. Insights into early pig domestication provided by ancient DNA analysis. Scientific Reports. 7, 44550. DOI: https://doi.org/10.1038/srep44550
[57] Pennisi, E., 2015. The taming of the pig took some wild turns - Porker's rendezvous with wild boar could overturn long-held theories about domestication. Available from: https://www.science.org/content/article/taming-pig-took-some-wild-turns (cited 16 November 2024).
[58] Giuffra, E., Kijas, J.M.H., Amarger, V., et al., 2000. The origin of the domestic pig: Independent domestication and subsequent introgression. Genetics. 154, 1785–1791.
[59] Pavid, K., 2019. Understanding the origins of European domestic pigs. Available from: https://www.nhm.ac.uk/discover/news/2019/august/understanding-the-origins-of-european-domestic-pigs.html (cited 16 November 2024).
[60] Mark, J.J., 2019. Pigs in Ancient China. Available from: https://www.worldhistory.org/article/1320/pigs-in-ancient-china/ (cited 16 November 2024).
[61] Gastrointestinal Society (GIS), Canadian Society of Intestinal Research (CSIR), 2024. Animal Digestive Systems. Available from: https://badgut.org/information-centre/a-z-digestive-topics/animal-digestive-systems/ (cited 14 November 2024).
[62] Parish, J.A., 2022. Understanding the Ruminant Animal Digestive System. Available from: http://extension.msstate.edu/sites/default/files/publications/publications/P2503_web.pdf (cited 16 November 2024).
[63] Wallen, J., 2024. Why is pork considered the dirtiest meat?. Available from: https://www.quora.com/Why-is-pork-considered-the-dirtiest-meat (cited 14 November 2024).
[64] Coller, K., 2022. Feral Swine Bomb: How wild pigs are threatening Canada's ecosystems and economy. Available from: https://www.youtube.com/watch?v=DLqLVX1dnAE (cited 14 November 2024).
[65] Cuevas, D., Cradic, M., Henry, A., 2021. Why is Pork Forbidden? Religion for Breakfast. Available from: https://www.youtube.com/watch?v=pI0ZUhBvIx4 (cited 14 November 2024).
[66] Sapir-Hen, L., Bar-Ozdot, G., Ga, Y., et al., 2013. Pig husbandry in iron age Israel and Judah: New insights regarding the origin of the taboo. Journal of the German Society for Exploration of Palestine. 129(1), 1–20. Available from: https://www.jstor.org/stable/43664894
[67] Statistics Canada, 2024. Farm product prices, crops and livestock. Table 32-10-0077-01. Available from: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210007701 (cited 16 November 2024).
[68] Statistics Canada, 2022. Canada's 2021 Census of Agriculture: A story about the transformation of the agriculture industry and adaptiveness of Canadian farmers (Tables 1 and 4). Component of Statistics Canada catalogue no. 11-001-X. Available from: https://www150.statcan.gc.ca/n1/en/daily-quotidien/220511/dq220511a-eng.pdf?st=vN9ezuGz (cited 16 November 2024).
[69] Canada Pork, 2024. On-farm Food Safety & Quality Assurance. Available from: https://canadapork.com/canadian-advantage/the-canadian-pork-commitment/on-farm-food-safety-quality-assurance/ (cited 17 November 2024).
[70] Canadian Food Inspection Agency, 2013. Trichinellosis - Fact Sheet. Available from: https://inspection.canada.ca/en/animal-health/terrestrial-animals/diseases/reportable/trichinellosis/fact-sheet (cited 14 November 2024).
[71] Van, D., 2011. Cooking Meat? Check the New Recommended Temperatures. Available from: https://www.usda.gov/media/blog/2011/05/25/cooking-meat-check-new-recommended-temperatures#:~:text=minute%20rest%20time (cited 16 November 2024).
[72] NBC News, 2009. Pork farmers: Stay away from our pigs!. May 1, 2009 Available from: https://www.nbcnews.com/id/wbna30507287 (cited 16 November 2024).
[73] Ontario Pork, 2019. Small Scale Pig Production: An introduction to small scale pig production in Ontario. Available from: https://www.ontariopork.on.ca/Portals/0/Small-Scale-Pig-Production-in-Ontario-Manual-November-21.pdf (cited 6 September 2024).
[74] Racewicz, P., Ludwiczak, A., Skrzypczak, E., et al., 2021. Welfare health and productivity in commercial pig herds. Animals. 11(4), 1176. DOI: https://doi.org/10.3390/ani11041176
[75] Redding, R.W., 2015. The pig and the chicken in the Middle East: Modeling Human subsistence behavior in the archaeological record using historical and animal husbandry data. Journal of Archaeological Research. 23(4), 325–368. DOI: https://doi.org/10.1007/s10814-015-9083-2
[76] Dyer, J.A., Vergé, X.P.C., Desjardins, R.L., et al., 2018. District scale GHG emission indicators for Canadian field crop and livestock production. Agronomy. 8(9), 190.

[77] Elward, M., McLaughlin, B., Alain, B., 2003. Livestock Feed Requirements Study 1999–2001. Catalogue No. 23-501-XIE, Statistics Canada, 84pp. Available from: https://www150.statcan.gc.ca/n1/en/catalogue/23-501-X2003001 (cited 17 November 2024).

[78] Statistics Canada, 2003. Livestock feed requirements study, 1999–2001. Statistics Canada Cat. No 23-501-XIE. Statistics Canada, Ottawa, Ontario, Canada. Available from: https://www150.statcan.gc.ca/n1/en/catalogue/23-501-X2003001 (cited 16 November 2024).

[79] Agriculture and Agri-Food Canada (AAFC), Science and Technology Branch, 2013. Interpolated Census of Agriculture. Available from: https://open.canada.ca/data/en/dataset/1dee8513-5c73-43b6-9446-25f7b985cd00 (cited 18 November 2024).

[80] Dyer, J.A., Desjardins, R.L., 2003. Simulated farm fieldwork, energy consumption and related greenhouse gas emissions in Canada. Biosystems Engineering. 85(4), 503–513. DOI: https://doi.org/10.1016/S1537-5110(03)00072-2

[81] Dyer, J.A., Desjardins, R.L., 2005. Analysis of trends in CO2 emissions from fossil fuel use for farm fieldwork related to harvesting annual crops and hay, changing tillage practices and reduced summerfallow in Canada. Journal of Sustainable Agriculture. 25(3), 141–156. DOI: https://doi.org/10.1300/J064v25n03_09

[82] Dyer, J.A., Desjardins, R.L., 2006. Carbon dioxide emissions associated with the manufacturing of tractors and farm machinery in Canada. Biosystems Engineering. 93(1), 107–118.

[83] Dyer, J.A., Desjardins, R.L., 2009. A review and evaluation of fossil energy and carbon dioxide emissions in Canadian agriculture. Journal of Sustainable Agriculture. 33(2), 210–228. DOI: https://doi.org/10.1080/10440040802660137

[84] IPCC, 2007. Climate Change 2007: The Physical Science Basis. Fourth Assessment Report (AR4), IPCC Working Group I., Cambridge University Press, Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paolo, Delhi. Available from: https://www.ipcc.ch/site/assets/uploads/2018/02/ar4-wg1-frontmatter-1.pdf (cited 16 November 2024)

[85] Statistics Canada, 2023. Fertilizer Shipments to Canadian Agriculture Markets, by Nutrient Content and Fertilizer Year, Cumulative data (×1000). Table: 32-10-0039-01. Available from: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210003901 (cited 16 November 2024).

[86] Dyer, J.A., Pearson, A., Desjardins, R.L., 2024. Interpolation of nitrogen fertilizer use in Canada from fertilizer use surveys. Agronomy. 14(8), 1700. DOI: https://doi.org/10.3390/agronomy14081700

[87] Dyer, J.A., Vergé, X.P.C., Desjardins, R.L., et al., 2015. Changes in greenhouse gas emissions from displacing cattle for biodiesel feedstock. In: Biernat, K. (ed). Biofuels - Status and Perspective, InTech Open Access Publisher: Rijeka, Croatia. pp. 351–375. Available from: https://www.intechopen.com/chapters/48376

[88] Statistics Canada, 2024a. Number of cattle, by class and farm type (x 1,000). Table 32-10-0130-01. Available from: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210013001 (cited 15 November 2024).

[89] Statistics Canada, 2024b. Hogs statistics, number of hogs on farms at end of semi-annual period (x 1,000). Table: 32-10-0160-01. Available from: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210016001 (cited 15 November 2024).

[90] Statistics Canada, 2006. Agriculture overview, Canada and the provinces - Pigs on Census Day, 2006 and 2001 (Table 1.25) Catalogue no. 95-629-XWE 15, Available from: https://www150.statcan.gc.ca/n1/pub/95-629-x/1/4123811-eng.htm (cited 15 November 2024).

[91] Culley, J.L.B., Barnett, G.M., 1984. Land disposal of manure in the province of Quebec. Canadian Journal of Soil Science. 64, 75–86. Available from: https://cdnsciencepub.com/doi/pdf/10.4141/cjss84-007

[92] Seppelt, R., Klotz, S., Peiter, E., et al., 2022. Agriculture and food security under a changing climate: An underestimated challenge. IScience. 25(12), 105551. DOI: https://doi.org/10.1016/j.isci.2022.105551

[93] Kenyon, S., 2020. What is Regenerative Grazing? From the Ground Up. Canadian Cattlemen. Available from: https://www.canadiancattlemen.ca/from-the-ground-up/what-is-regenerative-grazing/ (cited 18 November 2024).

[94] Allen, D., Schmitz, O.J., Sylven, M., 2022. Animating the Carbon Cycle. GRA Public. Series 2022/01. Available from: https://wild.org/wp-content/uploads/2022/03/GRA_ACC_2022_FINAL.pdf (cited 18 November 2024).

[95] American Criollo Beef Association, 2024. The Difference between Grass Fed and Grain Fed Beef - Go Against the Grain!. Available from: https://www.leanandtenderbeef.com/Blog/Grass-Fed-Beef/ (cited 18 October 2024).