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Carbon-Equivalent Taxes on US Meat

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ABSTRACT

Almost 6 percent of US greenhouse gas emissions come from methane and nitrous oxide in the livestock sector. This study calculates carbon-equivalent consumption taxes for beef, milk, pork and chicken that could accompany fossil-fuel taxes or regulations in the rest of the economy. Beef production is much more emissions-intensive than that of pork or chicken. At a social cost of carbon dioxide of $75 per ton, the carbon-equivalent tax would be about 20 percent on beef, 4 percent on milk, and about 3 percent on pork and chicken. Compensation to low-income households would be appropriate, as would partial exemption for certified farms and ranches once low-emission feeding and genetic techniques become clearer or widespread testing of animals for enteric methane becomes feasible.

Keywords: livestock emissions; carbon tax
(JEL D12, Q15, Q54)

Introduction

The United Nations Food and Agriculture Organization has estimated that in 2005 the livestock sector was responsible for 7.1 gigatons of carbon-dioxide-equivalent emissions ($GtCO_2$-eq), or 14.5 percent of total greenhouse gas emissions (FAO, 2013, p. 15). One-fifth of these emissions were from fossil fuel used in supply chains (p. xii), and so would be addressed by a general fossil-fuel carbon tax. Livestock is a relatively unique sector of activity, however, in that the bulk of its emissions is not from fossil fuels and would escape such a tax. A consumption tax on meat, analogous to a tax on gasoline at the pump, is arguably the most direct way to address the sector's emissions.

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[1] President, Economics International Inc., and Senior Fellow Emeritus, Peterson Institute for International Economics. This revision includes a new section on exemptions for low-emissions practices. The July 2020 version of this study is available on request. For comments, I thank without implicating Robert Mendelsohn and Richard Tol.

The largest emissions from livestock are in the form of methane (3.1 $GtCO_2$-eq annually) and nitrous oxide (2 $GtCO_2$-eq). There are also sizable carbon dioxide emissions from deforestation associated with pasture expansion, primarily in Latin America (FAO, 2013, p. 25).

Cattle account for 65 percent of total emissions from the livestock sector globally. Including indirect emissions, in 2005 beef was responsible for emissions amounting to 2.9 $GtCO_2$-eq, and milk, 1.9 $GtCO_2$-eq (FAO, 2013, p. 23). Of the 3.3 $GtCO_2$-eq direct emissions from cattle, 71 percent was in the form of methane released in enteric fermentation; 21 percent from manure-based nitrous oxide; and 4 percent from manure-based methane (Gerber et al, 2013, 221).

Enteric fermentation is a unique feature of emissions from cattle and other "ruminants" (including buffalo, sheep, and goats). The anaerobic fermentation of plant material in the digestive tract of ruminants yields methane as a byproduct, which the animal expels primarily through belching (FAO, 2020a).[2] Nitrous oxide emissions come from use of fertilizers for feed production and application of manure to pasture (FAO, 2020b). Manure contains organic matter which can be converted into methane, primarily when managed in liquid form (lagoons or holding tanks).

This study estimates carbon-equivalent taxes for the United States for beef, milk, pork, and chicken, set at levels designed to equate to the social cost of carbon dioxide. The estimates first consider the typical US levels of emissions per kilogram of meat (or milk), based on USDA (2014, 2016) estimates. They then apply benchmark carbon taxes per ton of carbon dioxide (from EPA, 2016) to arrive at the appropriate tax per kilogram of beef, milk, pork, or chicken.

As discussed below, there is considerable scope for reducing emissions from enteric fermentation and manure through improved feeding approaches, genetic selection, and other management practices. At present technical uncertainties and likely limits to the potential for such reductions suggest it would be difficult to establish a meaningful basis for certifying exemption from a meat tax on grounds of production using low-emissions practices. However, once best practices for low emissions are clearer, and emissions testing more widespread, certification and partial exemption could provide an important incentive for reducing emissions.

Following an analysis of the likely impact of carbon-equivalent taxes on consumption and emissions for beef, milk, pork and chicken; consideration of equity issues; and a comparison with other studies, this paper concludes with a summary of the principal findings and implications. Appendix A compares the estimates for the United States to corresponding estimates for North America as calculated by the FAO (2013).

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[2] The rumen is the largest of the four chambers in a ruminant's stomach.

Social Cost of Carbon Dioxide Equivalent

In 2016 the US Environmental Protection Agency provided updated estimates of the social cost of carbon dioxide for use in its rulemaking (EPA, 2016). It reported estimates using three alternative time discount rates: 5 percent, 3 percent, and 2.5 percent. Its corresponding estimates of the social cost of carbon dioxide (at 2007 prices) were \$12, \$42, and \$62 per ton of CO_2 respectively by 2020, and \$16, \$50, and \$73 by 2030.[3]

At a 2011 conference on the EPA's methodology, I argued that even its low-end discount rate was somewhat too high (Cline, 2011).[4] So the estimates here adopt the lowest of the EPA's discount rates (2.5 percent). On this basis, and adjusting for US inflation from the 2007 base, the social cost of carbon for 2020 amounts to \$75 per ton of carbon dioxide.[5] To place this price in perspective, it corresponds to a tax of about 67 cents per gallon on gasoline (23 percent ad valorem), \$32 per barrel of oil (47 percent), and \$194 per short ton of coal (almost 500 percent).[6]

US Livestock Emissions

Table 1 shows the summary estimates by the US Department of Agriculture for US livestock emissions in 2013, by sector and greenhouse gas. Several key characteristics of livestock emissions stand out. First, cattle by far dominate total emissions. The combined emissions of the beef and dairy sectors amounted to 300 mmt CO_2-eq in 2013, or 87.6 percent of total livestock emissions. Second, enteric fermentation accounts for almost half of total emissions. For cattle, it represents 158.7 mmt, or 53 percent of cattle-sector emissions. Third, by greenhouse gas, methane and nitrous oxide dominate livestock emissions, representing 66 percent and 33 percent of the total respectively.

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[3] Subsequently under the Trump administration the EPA revised its estimates down to a range of only \$1 to \$7 per ton of CO_2. It argued that only benefits to the United States, rather than globally, should be counted, ignoring benefits to the United States from abatement carried out by other countries and the need for reciprocity to elicit them. It also argued that the discount rates considered should be no lower than the 3 percent and 7 percent alternatives traditionally used for government analysis, even though global warming involves a horizon of at least two centuries rather than more typical project lives of a few decades. See Brad Plumer, "Trump Put a Low Cost on Carbon Emissions. Here's Why It Matters," *New York Times*, August 23, 2018.

[4] Following Ramsey (1928), the social discount rate equals the rate of per-capita consumption growth multiplied by the elasticity of marginal utility, and should make no additional allowance for "pure" time preference from impatience. With century-scale per capita growth of 1 percent annually, and elasticity of marginal utility at 1.5, the rate for discounting future consumption would be only 1.5 percent per year. Taking into account higher return on investment boosts this rate only modestly. See Cline (1992, chapter 6).

[5] The personal consumption expenditure (PCE) price index has risen by 20.3 percent from 2007 to June 2020 (FRED, 2020).

[6] Carbon dioxide emission coefficients are as follows: 8.89 kg CO_2/ gallon of gasoline (EIA, 2016); 0.43 mt CO_2/ barrel of oil (EPA, 2020b); 2.86 short tons CO_2/ short ton coal (1 short ton = 907.2 kg) (EIA, 2020a). Prices are: \$2.89/ gallon in April 2019 (BLS, 2020); \$57/ bbl West Texas International for 2019 (EIA, 2020c); and \$39.08/ short ton of coal delivered to electric utilities in 2018 (EIA, 2020b). For gasoline and oil, 2019 prices are more representative than those in 2020 during the coronavirus pandemic.

In contrast, the USDA estimates of emissions of carbon dioxide itself from livestock are a minimal 1 percent of the sector's total CO_2-equivalent emissions. This finding reflects the absence of supply-chain fossil fuel emissions in the USDA livestock emissions inventory (in contrast to their inclusion in the estimates of the FAO, 2013). Excluding supply-chain fossil fuel emissions is the appropriate approach if the policy framework is likely to involve the implementation of general fossil-fuel carbon taxes accompanied by supplementary consumption taxes on products intensive in emissions of greenhouse gases other than carbon dioxide. The de minimis CO_2 emissions also reflect the sharp contrast between livestock emissions in the United States and those in such countries as Brazil where deforestation and other land-use change for pasture expansion contributes major carbon dioxide emissions.

Table 1
US Livestock Emissions of Greenhouse Gases, 2013
(million metric tons of CO_2-equivalent)

	Cattle:		Swine	Poultry	Other	Total
	Beef	Dairy			(a)	
Enteric ferm. - CH_4	117.1	41.6	2.5	NA	3.4	164.5
Managed livestock waste:						
CH_4	0.6	31.7	23.1	3.2	0.1	58.6
N_2O	7.6	5.7	1.9	1.6	0.5	17.3
Grazed land:						
N_2O	85.2	5.1	0.2	0.2	5.3	95.9
CH_4	2.4	0.1	0	0	0.3	2.8
CO_2	3.0	0.2	0	0	0.2	3.3
Total	215.9	84.3	27.7	5.0	9.6	342.5
CH_4	120.1	73.4	25.6	3.2	3.8	225.9
N_2O	92.8	10.8	2.1	1.8	5.8	113.2
CO_2	3.0	0.2	0	0	0.2	3.3

a. Horses, sheep, goats, bison, mules, asses

Source: USDA (2016, p. 12)

Beef and Milk

Attributing cattle sector emissions to beef as opposed to milk is not straightforward, because whereas the beef subsector produces only meat, the dairy sector produces both meat and milk. The approach here is to divide dairy sector emissions between those identifiable as attributable to meat as a byproduct, and those attributable to milk (the remainder). The emissions intensity of the beef sector provides the basis for measuring emissions intensity per kilogram of beef. This approach also makes it necessary to divide beef production between the beef sector and the dairy sector.

Beef cattle are typically slaughtered at 30-42 months age, an average of 36 months (USDA, 2020c). Dairy cattle are typically slaughtered at 73-81 months age, an average of 77 months. The USDA defines calves as cattle of 1 year or younger (Beef2Live, 2020). By implication, an adult cow in the dairy sector has 65 months of maturity, whereas an adult on the beef sector has 24 months of maturity. For purposes of accounting the annual flow of cattle into the beef market, one dairy cow in the dairy population represents only 24/65 = 0.37 of one adult cow or steer in the beef sector. In its 2013 inventory, the USDA (2016, p. 32) placed the adult (non-calf) US cattle population at 14 million in the dairy sector and 47 million in the beef sector. The corresponding shares in the annual flow of slaughtered cattle would be 10 percent from the dairy sector and 90 percent from the beef sector.[7]

An alternative estimate by Boetel (2017) places the share of dairy cattle in annual meat production much higher, at 22.7 percent. The estimates here apply an average of these two alternatives, placing the beef sector as the source of 83.6 percent of annual beef meat and the dairy sector as the source of 16.4 percent.[8] Table 2 uses this apportionment to arrive at emissions intensities for beef meat and for milk. The calculations impute an identical emissions intensity for meat from the beef sector and meat from the dairy sector, even though the much longer age of dairy cattle would imply that cumulative feed and hence emissions per animal would be higher in dairy. Even so, consideration of the meat by-product in the dairy sector approximately cuts in half the total emissions in the sector attributable to milk itself.

Table 2
US Beef and Dairy Cattle Populations, Slaughter Ages,
Production, and CO_2-eq Emissions in 2013

	Beef	Dairy	Total
Adult cattle (mn) [a]	47	14	61
Slaughter age (mo)	36	77	45
Meat (mmt), carcass wt	9.76	1.91	11.67
Meat (mmt), retail wt	6.34	1.24	7.59
Milk (mmt)	0	91.26	91.26
Emissions (mmt CO2-eq)	215.87	84.34	300.2
Meat (mmt)	215.87	43.04	258.91
Milk (mmt)	0	41.3	41.3
Kg emissions / kg product			
Meat	34.43	34.43	34.43
Milk	…	0.45	0.45

a. Excludes 29 million calves

Calculated from USDA (2016, pp. 12, 32), USDA (2014, pp. 22-23)

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[7] That is: (0.37 x 14)/ [(0.37x14) + 47].

[8] Note that calves are not included. Annual production of veal is small, at 0.3 pounds per person in 2008 (USDA, 2020d) compared to total beef production of 81.4 pounds per person (USDA 2014, p. 22).

In 2013, US beef production amounted to 25,720 million pounds carcass weight (USDA, 2014, p. 22), or 11.67 million metric tons (mmt). Of total carcass weight, on average 65 percent is available for retail cuts of boneless trimmed beef (SDSU Extension, 2020).[9] On this basis, total meat available for retail cuts amounted to 7.58 mmt, with 6.34 mmt coming from the beef sector and 1.24 mmt from the dairy sector. Dividing the USDA estimate of 215.6 mmt CO_2-eq emissions from the beef sector by 6.34 mmt effective meat supply from that sector yields an emissions intensity of 34.4 kg CO_2-eq /kg beef. At a social cost of $75 per ton of carbon-dioxide equivalent, the corresponding tax would be $2.58 per kg of beef.[10]

The Bureau of Labor Statistics reports that in March 2020, the average US city price of beef was $4.36 per pound for ground beef, $5.54/lb for roasts, $7.68/lb for steaks, and $5.08 for all other beef (BLS, 2020). The weighted average price was $5.84 per pound, or $12.87 per kg (applying BLS, 2019 weights).[11] The carbon-equivalent tax on beef consistent with a social cost of carbon of $75 per ton of carbon-dioxide equivalent would thus represent a *tax rate of 20.1 percent*.[12]

After attributing about half of the dairy sector's emissions to the meat obtained from slaughter of dairy cows, the remaining half translates to an emissions intensity of 0.45 kg CO_2-eq/ kg milk. At $75 per metric ton of CO_2-eq emissions, the *carbon-equivalent tax on milk would be 3.38 cents per kg.*[13] With a gallon of milk containing 3.9 kilograms (Dairexnet, 2020), this tax would amount to *13.2 cents per gallon*. The BLS (2020) places the US city average price of milk in March 2020 at $3.25 per gallon. The carbon-equivalent tax would thus amount to *4.1 percent* for milk.

Pork and Chicken

As shown in table 1, the USDA (2016) places total greenhouse gas emissions from the swine sector at 27.7 mmt CO_2-eq in 2013. The USDA (2014) reports total production of pork in 2013 at 23,187 million pounds carcass weight, or 10.52 mmt. Pork meat in retail cuts is an average of 80 percent of carcass weight (ODA, 2020), placing production of edible meat at 8.42 mmt. The emissions intensity of pork is thus 3.29 kg CO_2-eq per kg meat available for retail cuts. At a social cost of carbon at 7.5 cents per kilogram the corresponding carbon-equilvalent *tax on pork would be 24.7 cents per kilogram*, or 11.2 cents per pound.

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[9] Carcass weight, in turn, is typically 63 percent of live animal weight.

[10] That is: 7.5 cents/kg x 34.43 kg emissions / kg meat.

[11] For 2015-16, expenditure category weights for beef were: 39.7% for ground beef, 14.4% for roasts, 37.2% for steaks, and 8.1% for all other. Calculated from BLS, 2019.

[12] That is: $2.58/12.87.

[13] That is: 7.5 cents x 0.45.

The BLS (2020) reports a weighted average retail price of $4.09 per pound of pork.[14] The tax would thus be only *2.7 percent* of retail value, strikingly lower than the tax for beef (and about two-thirds the ad valorem tax rate for milk).

For chicken, the USDA (2016) estimates for poultry place US emissions in 2013 at a total of 5 mmt (table 1). The USDA (2014) reports production of "broilers" in 2013 at 37,830 million pounds, and of turkeys, at 5,805 million pounds, for a total of 43,635 million pounds for poultry, or 19.8 mmt. For chicken, there is no need to convert these carcass weight data to edible meat equivalent. On this basis, the USDA estimates of emissions for the poultry sector were 0.25 kg CO_2-eq per kg of meat.

As discussed in Appendix A, for chicken the emissions intensity estimates of the FAO (2013) for North America differ in the extreme from those of the USDA (2016) for the United States.[15] The FAO places emissions at 4.32kg CO_2-eq /kg chicken meat. If only 20 percent of the FAO estimate is deducted to remove supply-chain fossil-fuel emissions (the FAO average for livestock), the intensity remains high at 3.46 kg, or 13.8 times as high as the USDA-based estimate. In contrast, as discussed in Appendix A, FAO-based emissions intensity estimates for North America are only modestly higher than the USDA-based estimates for the United States for beef (by 7 percent), and only moderately higher for pork (by 27 percent).

The FAO estimates for chicken production show that the sector has a disproportionately high share of supply-chain CO_2 emissions in the total, reflecting the absence of enteric fermentation emissions present for cattle (and other ruminants) and swine as well as relatively small emissions from poultry manure management. As discussed in Appendix A, after deducting sector-specific fossil-fuel CO_2 emissions for chicken associated with feed, indirect energy, direct energy, and post-farm processing and distribution, the FAO estimate of emissions intensity for North American chicken production falls to 2.17kg CO_2-eq/kg meat.[16] As the adjusted level is still more than eight times the USDA-based estimate (0.25 kg CO_2-eq/kg), for chicken the estimate used here is the average between that of the USDA-based and adjusted FAO-based measures, or *1.21 kg* CO_2*-eq/kg chicken meat*. At a carbon-equivalent tax of 7.5 cents per kilogram of CO_2-eq, the corresponding tax would be *9.1 cents per kilogram, or 4.1 cents per pound*.[17] The BLS (2020) shows the average retail price for a whole chicken in March 2020 as $1.40 per pound ($3.08 per kilogram). The carbon-equivalent tax would amount to a *2.9 percent tax* on retail value.

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[14] Price per pound and weights of sub-categories were: bacon, $5.26 (44.9%); ham, $3.38 (17.7%); chops, $3.42 (14.6%); other, $2.76 (22.8 percent).

[15] I thank Laura Gallagher, Environmental Policy Analyst at the US Department of Agriculture, for guidance on the difference between the USDA and FAO estimates.

[16] Calculated from FAO (2013, p. 36).

[17] That is, 2.29 x 7.5 = 17.2.

Overview for four products

As shown in table 1, the USDA estimates that 97.2 percent of US livestock emissions of greenhouse gases came from the four products examined here: beef, milk, pork, and poultry. Table 3 summarizes the calculations of this brief for appropriate carbon-equivalent taxes on beef, milk, pigs, and chickens.

Table 3

Carbon-equivalent Tax Estimates for Beef, Milk, Pork, and Chicken

	Beef	Milk	Pork	Chicken[a]
Emissions: kg CO_2-eq/kg	34.43	0.45	3.29	1.21
CO_2-eq tax (\$/kg) (a)	2.58	0.034	0.247	0.091
Retail unit	pound	gallon	pound	Pound
kg/ retail unit	0.4536	3.9	0.4536	0.4536
CO_2-eq tax /unit (\$)	1.17	0.132	0.112	0.041
Retail price (\$)	5.84	3.25	4.09	1.40
CO_2-eq tax % value	20.1	4.1	2.7	2.9

a. Average of USDA-based and adjusted FAO-based estimates.
b. For carbon tax of $75 per ton of carbon-dioxide-equivalent
Source: see tables 1, 2 and Appendix A.

Corresponding aggregates for the four products imply a relatively large contribution to US greenhouse gas emissions, as well as a sizable aggregate carbon-equivalent tax revenue base. Table 4 shows the annual levels of total US production for the four products in 2019.

When these production levels are applied to the USDA-based estimates of emissions per kilogram (or USDA- and FAO-based, for chicken), the result is an estimated 372.2 million metric tons of CO_2-eq emissions in 2019. Total US emissions from all sources in 2018 were 6,677 million metric tons of CO_2-eq (EPA, 2020a). The four main livestock products thus accounted for 5.6 percent of total emissions. The entire agricultural sector was responsible for 10 percent of US emissions (EPA, 2020a). As shown in table 4, beef and dairy production alone were responsible for an estimated 317.4 mmt of emissions, or 4.8 percent of total US emissions. Similarly applying the social cost of carbon-equivalent per kilogram of meat or milk estimated in table 3 (CO_2-eq tax /kg), the potential revenue base if consumption remained unchanged would amount to $27.9 billion annually, or 8.4 percent of the annual retail value base of $330 billion for the four products.

Table 4
Aggregate Emissions and Carbon-equivalent Revenue Base for
Four Livestock Products, 2019 [a]

	Beef	Milk	Pork	Chicken	sum
1Production (mmt) (b)	12.19	99.07	11.94	19.32	
Retail meat (mmt)	7.92	…	9.55	19.32	36.8
Emissions kg CO_2-eq/kg	34.43	0.45	3.29	1.21	
Total emissions (mmt CO_2-eq)	272.8	44.6	31.4	23.4	372.2
Retail price ($ /kg)	12.87	0.833	9.02	3.09	
Retail value base ($ billions)	102.0	82.5	86.2	59.70	330.4
CO_2-eq tax ($/kg)	2.58	0.034	0.247	0.091	
Tax revenue base ($ bn)	20.5	3.3	2.4	1.8	27.9

a. Production: 2019. Prices: March 2020
b. Carcass weight

Source: Calculated from USDA (2020a) and tables 1, 2, 3

Consumption Response to Carbon-equivalent Taxes

Gallet (2010a) has applied meta-statistical analysis to examine the price elasticity of demand for meat products. He places the price elasticities at -0.985 for beef, -0.913 for pork, and -0.778 for poultry.[18] When these elasticities are applied to the ad-valorem carbon-equivalent tax rates shown in table 3, the implication is that only the tax on beef would have a sizable impact on consumption: a decline of 19.8 percent. The direct impact of the tax on pork would be a reduction in consumption by only 2.47 percent; and for chicken, a decline by only 2.26 percent.

Indirect effects through substitution would tend to boost the consumption of pork and chicken, however. Bonnet, Bouramra-Mechemache, and Corre (2016) use consumer panel data for France to estimate the cross-price elasticity of demand for pork as a function of the price of beef at +0.2185 for pork, and the corresponding elasticity for chicken at +0.0488 (p. 12). The carbon-equivalent tax rates would boost the price of beef by 16.9 percent relative to the price of pork and by 16.7 percent against chicken. Applying these changes in relative prices to the cross-price elasticities, the substitution effect would raise demand for pork by 3.69 percent and demand for chicken by 0.81 percent. On this basis, the overall effect would be to raise demand by 1.22 percent for pork but decrease demand by 1.45 percent for chicken.

Applying these changes to the product-specific total emissions indicated in table 4, the overall effect for the three products would be that the carbon-equivalent taxes would reduce emissions by 54.01 mmt from the impact on beef, increase emissions by 0.38 mmt for pork, and

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[18] His estimates include -1.062 for lamb, -1.167 for fish, and -0.85 for meat as a whole (p. 269).

reduce emissions by 0.34 mmt for chicken. For the three meats combined, emissions would fall by 54.05 mmt, or by 16.5 percent. For milk, emissions would decline by an estimated 1.80 mmt.[19] The overall reduction in emissions for the four key livestock products would be 55.85 mmt, a cutback of 15.0 percent.

Overall, consideration of consumption responses suggests two major patterns. First, beef would by far account for the main impact in reducing emissions. This result reflects both the much higher tax for beef than for pork and chicken and the much higher share of beef in total emissions, as beef accounts for almost three-fourths of the total emissions for the four products shown in table 4 (including milk). Second, substitution away from beef toward pork and chicken would be insufficient to cause more than a marginal offset to the emissions abatement from beef.

A caveat to these estimates is that they may be overstated from being premised on unduly high price elasticities. Femenia (2019) calculates a weighted average own-price elasticity of only -0.57 for all meat and fish. Springmann et al (2016, supplementary tables 8 and 9) imply even lower price elasticities. They calculate that for high income countries, a carbon-equivalent tax of 26.6 percent ad valorem on beef would reduce consumption by only 6.9 percent, implying a price elasticity of only -0.26.[20]

Equity Considerations

Meat is a major source of food, and food is a basic good absorbing a larger share of income for the poor than for the rich. It is accordingly important to consider equity aspects of imposing a carbon-equivalent tax on meat.

Henry (2014) estimates that in 1984-2012, food at home accounted for 12 percent of consumption for the lowest after-tax income quintile of US households, 10.9 percent for the second-lowest, 9.25 percent for the third quintile, 8.2 percent for the fourth, and 6.4 percent for the highest quintile.[21] These estimates imply an income elasticity of 0.67 for food consumption; an elasticity below unity indicates a basic good.[22] An implication is that a general tax on food would represent almost twice as high a proportion of the household consumption budget for poorest 40 percent of households as for the richest 20 percent. Correspondingly, the

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[19] This calculation assumes the same price elasticity for milk as for beef (-0.985), and no substitution between milk and the three meats.

[20] Their implied price elasticities are even lower for milk (-0.13), pork (-0.13), and poultry (-0.22).

[21] Henry classifies food at home as a "necessity." In contrast, with "food away from home" comprising 5.8 percent of the consumption budget for both the lowest and second quintile but 6.4 percent for both the fourth and fifth quintile, it is placed into his other class, "luxury."

[22] After-tax income in 2012 was $30,000 per household for the second quintile and $160,000 per household for the fifth quintile (Henry, 2014, p.1). Saving can be estimated at about 3 percent of income for the second quintile and about 10 percent for the fifth quintile (based on Federal Reserve, 2016). Food was 11.9 percent of consumption for the second quintile and 6.4 percent for the fifth, or $3,169 and $9,216 respectively. The elasticity is calculated as $[(\ln c_5 - \ln c_2)/(\ln E_5 - \ln E_2)]$, where c = food consumption, E = total expenditure, and the subscript indicates the quintile.

lowest two quintiles account for 19.6 percent of total spending on food at home, whereas their share of after-tax income is only 12.9 percent.[23]

For meat, the regressive nature of a food tax might be mitigated if meat is a luxury component within the broad category of food. Estimates prepared at the USDA by Okrent and Alston (2012, p. 17) suggest, however, that the income elasticity of meat is not substantially higher than that of other food categories.[24]

Nonetheless, if meat taxes were levied on an ad-valorem basis, there would be some degree of inherent progressivity in allocating the carbon-equivalent tax burden. Because there are luxury and basic sub-categories within each meat category, applying the same percent of total price tax (i.e. an ad-valorem tax) would yield a higher absolute tax per kilogram for the luxury good and a lower absolute tax for the basic good. Within beef, the BLS (2020) reports the March 2020 price of regular ground beef at $3.88 per pound, but the price of lean and extra lean ground beef at $5.64 per pound. It shows steak at $7.68, and sirloin steak at $8.26 per pound. A pound of sirloin steak would generate more than twice the carbon-equivalent tax imposed on a pound of regular ground beef if the same ad-valorem rate were applied to both. A similar pattern exists for chicken. Higher income consumers are more likely to choose steak and chicken breasts; lower income consumers, ground beef and chicken wings (Lusk and Tonsor, 2015).

A potential source of moderating the regressiveness of a meat tax is that by far the highest tax would be levied on beef, and beef has the highest income elasticity of demand among the three major meats. In a meta-analysis of elasticity estimates for food demand, Femenia (2019) arrives at a weighted average income elasticity of 0.73 for meat and fish. This elasticity is broadly consistent with the overall food income elasticity of 0.67 identified in the rough estimate above. Within meat, a meta-analysis by Gallet (2010b) places beef at the highest income elasticity. He finds the rank order of income elasticities is 1.0 for beef, 0.97 for composite meat, 0.90 for fish, 0.82 for poultry, 0.80 for pork, and 0.74 for lamb (p. 484). If an overall income elasticity of 0.73 is applied, the corresponding product-specific elasticities would be 0.75 for beef, 0.71 for composite meat, 0.66 for fish, 0.60 for poultry, 0.58 for pork, and 0.54 for lamb.

If the product profile of meat consumption were identical to that of all food-at-home consumption at all income levels, given the 19.6 percent calculated above for the share of the bottom two quintiles they would also be expected to bear 20 percent of the total tax burden from a carbon-equivalent tax. Application of the rough estimates of income elasticities above (0.75 for beef, 0.58 for pork, and 0.60 for chicken) yields the result that the first two quintiles

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[23] Average household spending on food would be $1,318 in the first quintile, $3,169 in the second, $3,524 in the third, $5,667 in the fourth, and $9,216 in the fifth. The combined food spending of the first two would then equal only 19.6 percent of total spending on food.

[24] Their estimate for the elasticity of meat consumption with respect to total expenditure is at the median among their 7 broad food categories (of which one is food away from home). Note, however, that all of their expenditure elasticities are implausibly low (a simple average of 0.07).

account for 20.0 percent of spending on beef, 23.7 percent of spending on pork, and 23.3 percent of spending on chicken, or 22.1 percent for the three meats combined. So spending for the three meats tends to turn out to be proportionately higher for the first two quintiles than expected from overall spending on food at home.

However, the high-emissions intensity of beef means that its carbon-equivalent tax rate (about 20 percent ad-valorem) is much higher than that for pork (2.7 percent) or chicken (2.9 percent; table 3). As a consequence, the share of the first two quintiles in the carbon-equivalent tax revenue base would only be 20.7 percent (rather than their 22.1 percent share in spending on the three meats). The higher tax on beef would thus provide some moderation of the regressivity of the carbon-equivalent meat tax, but not a great deal.

Some form of transfer out of the carbon-tax revenue could be made to the two lowest quintiles of households to address the distributional impact. The calculations here suggest that such a compensation would amount to about 20 percent of the revenue base, or about $5.6 billion for the three meat products plus milk.

Tax exemption for certified low-emissions practices?

Feeding, breeding, and manure management are the principal domains for reducing emissions intensity of livestock. Enteric fermentation in cattle and other ruminants produces methane (CH_4) through the anaerobic decomposition of carbohydrates or acetic acid; or the combination of hydrogen and carbon dioxide.[25] The single-cell organism "archaea," a prokaryote (no nucleus), is instrumental in this methanogenesis. Methane-reducing practices therefore include feed supplements and treatments that reduce the relative presence of archaea protozoa, hydrogen, and acetic acid.

Feeding lipids (fatty acids, oils, seeds, tallow) inhibits methanogens by increasing salts of propionic acid relative to those of acetic acid. Removal of protozoa from the rumen (defaunation) through chemical feed supplements such as copper sulfate curbs hydrogen provided by protozoa for reduction of carbon dioxide into methane. The antibiotic monensin, widely used in ruminant feed, inhibits protozoa and methanogensis, although it is banned in the European Union (Hook, Wright, and McBride, 2010).[26]

A survey by Knapp et al (2014) finds that nutrition and feeding approaches might reduce methane emissions from enteric fermentation by 2.5 to 15 percent for dairy production, and that reductions of 15-30 percent can be achieved "by combinations of genetic and management

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[25] A carbohydrate is composed of carbon, hydrogen, and oxygen in the ratios 1:2:1. Decomposition of the carbohydrate glucose yields acetic acid, carbon dioxide, and methane. Thus: $C_6H_{12}O_6 \rightarrow 2CH_3COOH + CO_2 + CH_4$. Decomposition of acetic acid yields carbon dioxide and methane: $CH_3COOH \rightarrow CO_2 + CH_4$. The combination of hydrogen and carbon dioxide yields water and methane: $4H_2 + CO_2 \rightarrow 2H_2O + CH_4$. Conrad, 1999 (195).

[26] A monensin supplement reduces methane emissions by about 30 percent and ciliate protozoal population by about 80 percent for a few weeks, but the protozoa then adapt, leaving only about a 7-9 percent reduction in methane emissions with long-term supplementation (pp. 6-7).

approaches" (p. 3231) – albeit not necessarily in an additive or profitable fashion. A review by Broucek (2014) cites various numbers that imply an extremely wide range of emissions intensity, but the study reports much more moderate potential ranges in controlled comparisons.[27] A comprehensive survey by Gerber et al (2013) is replete with caveats and provides no summary measures of the reduction in emissions that might be expected from a shift to low-emissions practices.[28] There have been recent experiments showing promise for sharply reducing methane emissions by adding the seaweed *asparagopsis taxiformis* to cattle feed. However, the large scale of aquaculture cultivation that would be required to reduce emissions substantially makes this abatement alternative still questionable.[29]

Selective breeding has been a major factor in increasing milk yields. A near-doubling in yields from 1957 to 1997 permitted US milk production to rise from 118 billion pounds annually to 163 billion, even as the number of dairy cows fell from 12 million to 9 million. Permanent genetic change from selective breeding using high-ranking animal-improvement bulls was responsible for an estimated 57 percent of this yield increase (Cassell, 2001).

Roehe et al (2016) have conducted experiments aimed at improving cattle breeding for reduced methane emissions as well as greater feed conversion efficiency. Of nearly 4,000 genes, they identified 20 significantly associated with methane emissions. Among 5 Aberdeen Angus and 4 Limousin sire progeny groups, they found methane emissions (grams per day) for the lowest group were 24 percent below the average (and 34 percent below the highest group; their figure 2), suggesting significant scope for methane reduction.[30] They emphasize that "A fundamental problem is that ruminal microbiota is able to adapt rapidly to intervention methods that have been tried so far – such as different dietary formulations, chemical and biological feed additives, chemo-genomics and anti-methanogen vaccines" (p. 68). By implication, their breeding-genetic approach might be more resilient.

For reduction of methane emissions from manure lagoons, "dairy digesters" may provide a useful approach, albeit mainly for large-scale operations. In this process, a pit of liquid manure is covered. An anaerobic digester captures methane emissions and converts them to biogas, used to generate electricity or natural gas (EPA, 2011; Wozniacka, 2020).

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[27] Broucek cites methane emissions in dairy cows ranging from about 150 to 500 grams per day, but the variability reflects such factors as whether cows are lactating (p. 1482). In contrast, he cites a study finding low-forage feeding reduces methane reduction by only 13 percent in comparison to high-forage feeding on the same farm.

[28] Whereas "lipids [fatty acids insoluble in water but soluble in organic solvents] are effective in reducing enteric CH_4 emission, … [their] feasibility … depends on affordability … and potential negative effects … for example , reduction in fibre digestibility" (Gerber et al, p. 224). Ionophores (antibiotics) can increase feed efficiency by 2.5 to 15 percent but are banned in the European Union. Nitrate feed supplements have been shown to cut methane production by as much as 50 percent, but are primarily attractive in developing countries where forage has negligible levels of nitrate, and are potentially toxic when large amounts are eaten in a short period of time.

[29] See Judith Lewis Mernit, "How Eating Seaweed Can Help Cows to Belch Less Methane," *Yale Environment 360*, July 1, 2018, and "Seaweed feed additive cuts livestock methane but poses questions," *ScienceDaily*, June 17, 2019.

[30] The ratio of archaea to bacteria was also found to be highly correlated with methane emissions per day. Methanogenic archaea produce methane in ruminants.

At present, both the desired nature of best practices for low-emissions livestock and the depth of emissions avoidance they can be expected to achieve appear sufficiently uncertain that it is unclear that a meaningful program of certification could be developed to provide a basis for meat-tax exemption. As greater certainty is obtained, however, certification for low-emissions practices might become feasible as the basis for partial exemption from a meat tax, to provide an incentive for the adoption of such practices. One approach to certification could be on-farm inspections testing cattle for methane emissions, focusing on successful low-emissions outcomes rather than processes.[31] Periodic testing of automobile emissions arguably represents a precedent.

Comparison to other studies

Springmann et al (2016) provide an important set of estimates of the impact of a carbon-equivalent tax for food products on emissions as well as health by major global region. They apply a social cost of carbon of \$52 /kg CO_2-eq, based on the EPA (2016) estimate using a discount rate of 3 percent. They apply the FAO (2013) emissions intensities. For beef, they identify a carbon-equivalent tax for 2020 amounting to \$2.81/kg for the global average and \$1.39/kg for high income countries (HICs; their supplementary table 7). After taking account of the higher social cost of carbon applied in the present study (\$75/kg CO_2-eq) and considering the higher emissions intensity of beef in the United States than in Western Europe, their HIC emissions-intensity estimate is broadly consistent with the estimate here of \$2.58/ kg for the United States.[32]

The corresponding HIC carbon-dioxide-equivalent taxes per kilogram identified by Springmann et al (2016, supplementary table 7) are \$0.21/kg for milk, \$0.30 for pork, and \$0.30 for poultry. The tax identified here is relatively similar for pork (\$0.247 /kg) but much lower for milk (\$0.034) and poultry (\$0.091). For milk it is likely that the difference reflects the approach here of attributing about half of emissions of the dairy sector to the beef meat derived from it. For poultry, the difference likely reflects the large divergence between the FAO (2013) estimates and those here, primarily associated with the removal of supply-chain fossil-fuel emissions in the present study on grounds that they would already be covered by a tax on fossil fuels.

Springmann et al (2016) also address health consequences, and broadly find that improvements from dietary shifts from red meat to fruits and vegetables would exceed adverse effects from reduced food consumption except in lower- and middle-income countries in Africa and South-east Asia. They find that constraining tax coverage combined with income compensation or subsidies to fruits and vegetables turned net health effects positive in those

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[31] Garnsworthy et al (2019) identify six alternative methods of measuring methane output by individual animals, ranging from the expensive “gold standard” respiration chamber to low-cost breath sampling during milking and feeding. Although their objective is to facilitate testing for genetic differences, the methods could be applied to certification programs, perhaps with the respiration chamber required for large enterprises.

[32] The higher social cost would boost their estimate to [(75/52) x \$1.39] = \$2.00. The FAO (2013, p. 25) estimates North American emissions intensity for beef at about 50 percent higher than that in Western Europe.

two regions as well. Overall they estimate that a regionally optimized set of taxes would achieve 92 percent of the 1.0 GtCO$_2$-eq global emissions reduction from taxes on all food products. They also find that two-thirds of total emissions reductions would stem from the beef sector alone, and another 25 percent from the dairy sector. The high concentration of emissions reduction in beef and milk is consistent with the two sectors' combined share of 85 percent in the total emissions for the four products shown in table 4 above.

An important finding in their study is that overall food sector emissions would be cut by only 9 percent by carbon-equivalent taxes. An implication is that it would be important to channel much of the tax revenue to uses that would contribute indirectly to additional emissions reduction, including investment in non-carbon technologies both in and outside of agriculture.

Bonnet, Bouamra-Mechemache, and Corre (2016) examine the impact of carbon-equivalent taxes on meat in France. They estimate own-price elasticities and cross-price elasticities for pork, beef, chicken, other poultry, other meat, and fish. The authors use detailed product-specific estimates of emissions intensities in France, provided by a French environmental company. They report emissions of 15.89 kg CO$_2$-eq/kg for beef, 5.21 kg/kg for pork, and 7.42 kg/kg for chicken (p. 15).[33] For the key sector of beef their intensity is less than half the level estimated here for the United States (34.43 kg emissions/ kg beef; table 4). Their intensities are somewhat higher than those applied here for pork (3.29 kg CO$_2$-eq/ kg meat) and especially chicken (1.21). They consider two carbon prices: €56 and €200 ($62 and $224) per ton of carbon-dioxide-equivalent.[34] They indicate that these two levels correspond to estimates of carbon prices needed to achieve the EU policy goal of reducing economy-wide emissions by 20 percent from 1990 levels by 2020 and 60 percent by 2050 (p. 3).

The authors place the ad-valorem carbon equivalent tax for beef at an average of 9 percent, slightly less than half that in the present study, reflecting their lower emissions intensity and lower 2020 price of carbon-dioxide.[35] If all meat and marine products are taxed at €56/kg CO$_2$-eq, greenhouse gas emissions from the sector decline by only 1.54 percent (p. 4). This estimate is far below the 16.5 percent reduction in combined emissions for beef, pork, and chicken estimated above for the US, as well as the 9 percent reduction for all foodstuffs estimated by Springmann et al (2016). The low impact on emissions appears to be driven not only by the lower emissions intensity for and tax rate for beef than estimated here, but also by the small share of beef in the French food market compared to that in the US. Thus, for beef, pork, and chicken, beef accounts for 41 percent of market value in the United States, but only 13.5 percent in the French market.[36]

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[33] A somewhat lower intensity for France than the US would be consistent with the FAO (2013, 25) estimate that the emissions intensity for beef in Western Europe is only about two-thirds as high as that in North America.

[34] The average exchange rate in 2016 was 0.904 euro per US dollar. BIS (2020).

[35] An average tax rate of 9 percent for beef is implied by their 8.8 percent reduction in consumption if only beef is taxed (p. 18), given its own-price elasticity of -0.98 (p. 12).

[36] Calculated from table 4 for the US and p. 18 from Bonnet et al (2016), and including other poultry for France.

Conclusion

The four major livestock products (beef, milk, pork, and chicken) account for almost 6 percent of total US greenhouse gas emissions. Yet because about two-thirds of livestock emissions are in the form of methane and one-third in nitrous oxide (table 1), they would escape taxes or regulatory standards on fossil fuels. This study estimates carbon-equivalent consumption taxes for meat and milk that would incorporate livestock into future abatement policies.

Cattle are by far the most important source of livestock emissions, accounting for 88 percent (table 1). Greenhouse gas emissions are much higher for beef (34 kg CO_2-equivalent/kg meat) than for pork (3.3 kg emissions) or chicken (1.2 kg). About half of emissions from cattle are in methane emitted in digesting plant material ("enteric fermentation"). This study finds that *a carbon-equivalent consumption tax on beef of about 20 percent ad-valorem (or about $1.20 per pound)* would be needed to reflect the global-warming social cost of beef production in the United States. Such a tax would only be appropriate within a general framework of comparable carbon taxes applicable to fossil fuels.

The carbon-equivalent tax would be about 3 percent for both pork (11 cents per pound) and chicken (4 cents per pound), and about 4 percent for milk (13 cents per gallon; table 3).[37] After taking account of substitution away from beef to pork and chicken, total emissions from the four products (and hence approximately for livestock as a whole) would decline by about 15 percent, almost entirely from the reduction in beef and dairy emissions.

The revenue base from the carbon-equivalent taxes on meat and milk would be $28 billion annually, or about $24 billion after taking account of consumption adjustment.[38] One-fifth of revenue would appropriately be recycled to households in the bottom two quintiles of the income distribution to offset their higher costs. The bulk of revenue would appropriately be channeled to investment in carbon-saving technological change.

A 20 percent tax on beef would be approximately the same as the 23 percent ad valorem tax calculated above for gasoline using the same carbon-equivalent tax ($75 per ton of carbon-dioxide). Personal vehicles account for one-fifth of total US greenhouse gas emissions (UCS, 2014). Beef accounts for emissions about one-fifth as large as total US vehicle emissions.[39] There is no compelling reason why a serious national program to curb greenhouse gas emissions should exclude livestock emissions, especially from beef (which, including beef from dairy cows, accounts for almost three-fourths of total emissions from livestock; table 4). A consumption tax would appear to be the most feasible way to ensure livestock emissions are

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[37] About half of the emissions from the dairy sector would be covered by the tax on beef meat from dairy cows.

[38] As discussed above, response to price increases would reduce consumption and emissions by about 15 percent, mainly through the direct effect on beef but also from the indirect effect of shifting consumption from high-emissions beef to lower-emissions pork and chicken.

[39] One fifth of total emissions amounts to 1.34 $GtCO_2$-eq annually (UCS, 2014). Beef accounts for 0.273 $GtCO_2$-eq emissions annually (table 4).

addressed. Eventually, as best practices in feeding and breeding to attain low-emissions production become clearer, and/or as testing for animals' emissions becomes more widespread, certification for partial tax exemption could provide incentives for reducing emissions.

Appendix A

Comparison of US Emission Intensities to FAO Estimates for North America

The FAO (2013) has made estimates of greenhouse gas emission intensity for livestock production in 9 major regions.[40] Its estimates for North America provide a useful basis for comparison against the US estimates prepared in this study. A general feature of the FAO estimates is that they incorporate supply-chain fossil fuel emissions, which the FAO places at typically 20 percent of greenhouse-gas emissions in livestock. The estimates of this study are premised on consumption taxes of animal products that would be supplementary to carbon taxes on fossil fuels, with the latter either levied at the consumption level (e.g. special gasoline and diesel taxes at the pump) or the producer level (e.g. electricity companies).

The FAO (2013, p. 25) estimates that in North America, providing 1 kilogram carcass weight of beef generates 30 kg in carbon-dioxide-equivalent (CO_2-eq) greenhouse gases.[41] Removing the 20 percent associated with fossil fuel emissions in the supply chain, this estimate translates to 24 kg CO_2-eq. With meat available for retail cuts representing 65 percent of carcass weight, the FAO-based emissions amount to 36.9 kg CO_2-eq per kilogram of retail beef cuts.[42] The FAO estimate is thus broadly similar to the 34.4 kg emissions intensity derived from the USDA estimates (see table 2 above).

For milk, the FAO estimates that North-American production generates 1.7 kg CO_2-eq emissions per kilogram of cattle milk (FAO, 2013, p. 26). Net of the 20 percent for supply-chain fossil fuel emissions, emissions would amount to 1.36 kg CO_2-eq per kilogram of milk. This estimate is 3 times as large as the estimate of the present study (0.45 kg CO_2-eq /kg milk; table 2). A major reason would appear to be the fact that the FAO attributes the entirety of dairy sector emissions to milk (and other milk-based products) and does not separate out the beef production resulting from the slaughter of dairy cattle. Yet a meat tax at the consumer level would fall on meat produced from dairy cows, not on milk.

The FAO (2013, p. 36) places North American emissions from pork production at 4.18 kg CO_2-eq per kilogram of carcass weight. Meat available for retail cuts is 80 percent of carcass weight. After reducing the emissions estimate by 20 percent to remove supply-chain fossil-fuel emissions, the net emissions per kilogram of retail pork also amount to 4.18 kg CO_2eq/kg. In comparison, the estimate of this study is that pork generates greenhouse gas emissions of 3.29 kg CO_2eq/kg pork (table 4 above). The FAO-based estimate for North America is 27 percent higher than the estimate here.

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[40] North America, Latin America and the Caribbean, Western Europe, Eastern Europe, Russia, Near East & North Africa, Sub-Saharan Africa, South Asia, East & South East Asia, and Oceania.

[41] The emission rate reaches 70 kg CO_2-eq per kilogram of carcass weight in Latin America, driven by high land-use change emissions, and 70 to 75 kg CO_2-eq in Sub-Saharan Africa and South Asia, driven by high enteric fermentation emissions.

[42] That is: 24/0.65.

For chicken, in the FAO estimates North American emissions amount to 4.32 kg CO_2-eq per kilogram of carcass weight (FAO, 2013, p. 38). However, as noted in the main text, fossil-fuel carbon dioxide emissions attributed to chicken production are exceptionally high as a percent of the total. The FAO attributes the following CO_2 emissions per kg carcass weight: feed (1.2 kg); direct energy (0.5 kg); post-farm (0.43 kg); and indirect energy (0.1 kg). Once these emissions are deducted (assuming that fossil fuel emissions would be taxed separately in a general approach to taxing greenhouse gas emissions), the North American emissions intensity would fall to 2.17 kg CO_2-eq /kg.

No significant allowance would seem necessary for chicken for the conversion of carcass weight to retail meat weight, so this level of emissions also applies to retail meat. Even after cutting the FAO estimate approximately in half, the divergence between the (adjusted) FAO estimate and the USDA estimate remains extreme. The USDA-based estimate in table 2 above is only 0.25 kg CO_2-eq /kg chicken meat, whereas the adjusted FAO-based is almost 9 times this level. The calculations in this study apply the simple average of the USDA (0.25) and the adjusted-FAO estimate (2.17), or *1.21 kg* CO_2*-eq /kg chicken meat* (table 3 above).

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