Carbon and Slaughter Taxes for Meat: Modelling trade-offs between climate change and animal welfare

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Abstract

To reduce food systems emissions, economists and policymakers have called for carbon pricing on food products. This climate policy could lead to substitution away from carbon-intensive products from larger animals (beef, pork) to less carbon-intensive products from smaller animals (chicken, farmed fish). This can result in an increase in the total number of slaughtered animals and the total duration of their suffering. This study models this *Small Animal Replacement Problem* using a supply and demand model with constant elasticities. It then calibrates the model with data for the United States. The calibrated model predicts that a food carbon tax will cause a small decrease in the number of slaughtered animals and the duration of their suffering. This result is compared to a tax per slaughtered animal, for which the results predict a small decrease in greenhouse gas emissions. When an animal's death is valued at 10% of the Social Cost of Carbon or higher, a slaughter tax would be more tax-efficient at reducing external costs than a carbon tax. A meat and fish tax could be an easier-to-implement alternative to carbon and slaughter taxation when reducing greenhouse gas emissions and animal suffering are considered approximately equally important.

Keywords: animal suffering, animal welfare economics, multiple market failure, product substitution, price elasticity, meat, carbon pricing, elasticity-based modelling

JEL codes: C53, D11, H23, Q18, Q51

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1. Introduction

1.1 External costs of animal products

The market for animal products involves considerable external costs. The production of animal-based food accounts for 57% of total emissions from food (Xu et al., 2021), which itself contributes 19%-29% of anthropogenic greenhouse gas (GHG) emissions (Vermeulen et al., 2012). This implies that animal-based food production is responsible for approximately 14% of emissions.

Animal welfare should be considered in economic analysis, too. Animal welfare can be considered a public good when people derive utility from knowing that animals are treated humanely, even for products that they did not buy themselves (Espinosa & Treich, 2024; Lusk, 2011). It can also be regarded as an intrinsic good. Utilitarian ethics, foundational to mainstream economic theory, acknowledges the moral patienthood of animals because of their capacity to suffer (Bentham, 1789, Chapter XVII §1.IV; Singer, 1975). With over 80 billion land animals slaughtered for food per year (FAO, 2023), it becomes important to take animal welfare into account in the economics of food.

Among these two market failures, climate change has received the most attention from economists and policymakers. A primary economic tool to address this externality is carbon pricing by means of a tax or tradeable permit (Nordgren et al., 2012).[1] However, most carbon pricing policies do not cover agricultural and land use emissions, apart from agricultural fuel use (World Bank, 2024). These sectors are typically exempted because of distributional concerns (Grosjean et al., 2018) or political sensitivity (Clapp et al., 2018). Nonetheless, some countries, like Denmark, are considering or developing agricultural carbon pricing (TAPP Coalition, 2024). For this reason, it becomes worthwhile to ask how carbon pricing could affect animal welfare.

1.2 The Small Animal Replacement Problem

Policies aimed at mitigating climate change can affect animal welfare both negatively and positively. Negative effects include feed changes and reductions in grazing, genetic selection for yield or productivity, biotechnologies promoting growth and yield, and species shifts towards smaller and monogastric animals (Shields & Orme-Evans, 2015). As visible in Figure 1, the production and consumption of pork and chicken causes much lower greenhouse gas emissions than beef but requires more animals to produce the same amount of meat. A consumption shift towards smaller animals would increase the number of animals in livestock and aquaculture systems, and therefore increase animal suffering on the extensive margin.[2] Among animal welfare organisations, this effect is known as the *Small Animal Replacement Problem* (Charity Entrepreneurship, 2018; Nicholles, 2024).

[1] For simplicity, I use the term 'carbon price' for a price on all GHG emissions, expressed in USD/tonne CO_2- eq.

[2] The intensive margin refers to how much a farm animal suffers, while the extensive margin refers to how many animals suffer.

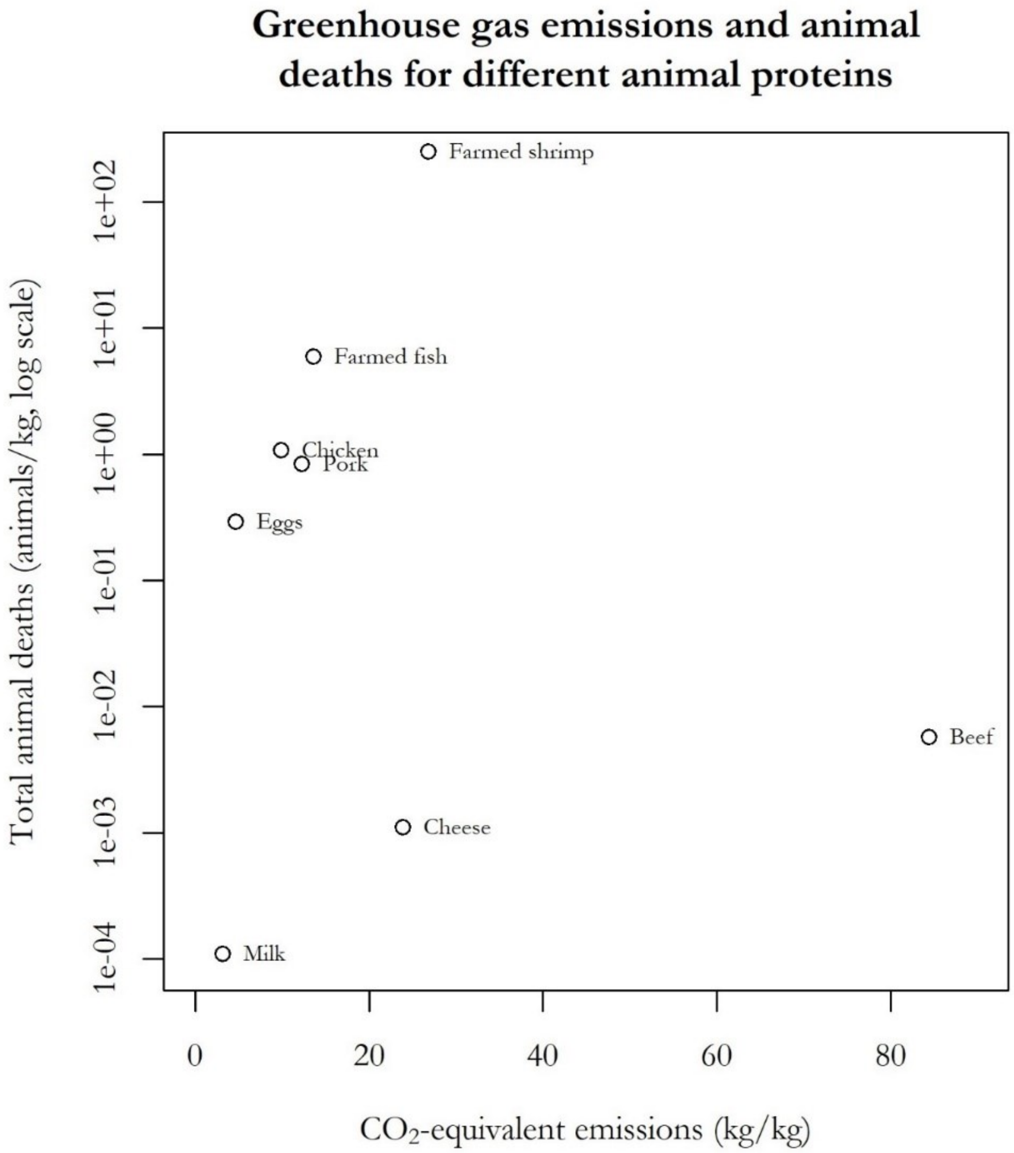

Figure 1. *Scatterplot of greenhouse gas emissions and animal deaths for different animal products. Data for greenhouse gas emissions are from Poore and Nemecek (2018), where the entry for beef is a mix between dairy herd (22.7%) and beef herd (77.3%) according to proportions specified by Geiser and Boetel (2017). Data on animal deaths are from Faunalytics (2022) with further processing by the author.*

The externality trade-offs between beef and chicken are modelled by Kuruc and McFadden (2023). Assuming that animal lives in livestock farming are worse than non-existence, they modify the DICE-FARM model to compare the climate and environmental externalities of the food sector. Their results show that the external costs for beef are lower than chicken when the Social Cost of Carbon (SCC) reaches thousands of U.S. dollars (USD) per tonne CO_2-equivalent (eq.), and the moral weight of animals relative to humans is only several percent.

1.2.1 Small Animal Replacement Problem for carbon taxation

Internalising the climate change externality of food with a carbon tax affects the extensive margin of animal suffering in two ways. First, the tax incentivizes reductions in all types of animal products, as all are taxed to some extent. Second, the carbon tax incentivizes substitution of carbon-intensive animal products, like beef, with less carbon-intensive products from smaller animals, like chicken. Depending on the magnitude of these effects, a carbon tax could (a) reduce overall consumption of all animal products and the number of killed animals, (b) lead to a net-decrease in the number of killed animals despite increased consumption of some products, or (c) result in a net-increase in the number of animals killed due to product substitution. Similarly, a tax per slaughtered animal can invertedly increase greenhouse gas emissions. Depending on the weight that a social planner attaches to climate damages versus animal welfare, carbon or slaughter taxes can even result in a net increase in external costs.

1.3 Elasticity-based modelling of external costs

Elasticity-based modelling, which uses data on the responsiveness of supply and/or demand to price changes, is frequently used to predict the effect of taxes on consumption and substitution. It is particularly useful when empirical data on policy effects are not available, such as when a policy is yet to be enacted. This makes it well-suited for studying the effects of carbon pricing on food.

Several studies have used elasticity-based modelling to examine carbon pricing on food. For example, Edjabou and Smed (2013) and Chalmers et al. (2016) model the expected effects of a carbon tax on food products in Denmark and Scotland, respectively. Elasticity-based models also predict that carbon taxation could negatively affect chronic diseases (Briggs et al., 2013), decrease the health impacts of soda consumption (Briggs et al., 2016), or reduce the intake of some nutrients (Kehlbacher et al., 2016; Revoredo-Giha et al., 2018).

The effects of carbon taxation on animal welfare remain under-researched, though some grey literature has explored the topic. A report by Animal Ask used product substitution data from previous studies in the United Kingdom and the European Union. In four of the nine scenarios that they studied, a carbon tax increased *animal-years consumed*, a metric combining the number of slaughtered animals with their average lifespan (Ryba, 2022). However, this study relies on previous research and lacks a formal theoretical foundation for testing different assumptions, tax levels, or robustness. A self-published manuscript by Bruers (2024) models substitution between animal products using elasticities and increased animal suffering. However, it assumes a perfectly elastic supply of animal products, inconsistent with empirical literature (Dey et al., 2007; Marsh, 1994; Muth et al., 2006, 2007). Moreover, its linear demand assumption may be unrealistic for larger price changes, as it will predict zero or negative demand.

1.4 Aim and contribution

This study examines the anticipated and comparative effects of carbon, slaughter, and meat taxation of animal products on carbon emissions and animal welfare. It addresses a gap in the existing literature concerning the unintended effects of carbon taxation of food by modelling the effect on animal welfare. Compared to existing studies on carbon taxation and animal welfare, it contributes by formalising the *Small Animal Replacement Problem* using a market model with constant supply and demand elasticities, including substitution between meat and fish.

I develop a supply and demand model for four animal products: beef, pork, chicken, and farmed fish (Section 2). The direct effects of excise taxation are captured using own-price elasticities, while substitution effects are modelled with the cross-price elasticity of demand. I then calibrate this model for the United States (U.S.) with data (Section 3) on the animal deaths per kilogram (kg), the number of days of suffering per kg, carbon emissions per kg, elasticities from the economic literature, food prices per kg, and current quantities sold. For simplicity, I ignore other sources of market failure and distributional effects. Results (Section 4) show no increase in animal suffering from a carbon tax, although a slaughter tax may be more tax-efficient at reducing external costs depending on the relative importance of the externalities. Section 5 discusses implications, and Section 6 concludes.

2. Method and model

2.1 Tax level

Let τ_i be the excise tax rate per kg of product sold of product i, C_e the cost of emitting 1 tonne of CO_2-eq. GHG emissions, C_m the additional cost per kg of meat or farmed fish, and C_k the additional cost of slaughtering an animal, all measured in USD. Let CI_i be the CO_2-eq. GHG emissions per kg of edible food product in kg, and AI_i the number of animals needed per kg of edible food product. The evaluated tax scenarios are presented in Table 1.

Table 1. *Overview of tax scenarios evaluated in this study*

#	Tax type	Description	Value of τ_i	Main tax level (alternatives)
1	Carbon tax	A tax on the average GHG emissions per kg	$\tau_i = \frac{C_e}{1000} \times CI_i$ (2.1.1)	\$25 (\$10, \$ 50) USD/tonne CO_2-eq.
2	Slaughter tax	A tax on the average number of slaughtered animals per kg	$\tau_i = C_k \times AI_i$ (2.1.2)	\$2.50 (\$1, \$5) USD/animal
3	Meat tax	A tax on all meat and fish products per kg	$\tau_i = C_m$ (2.1.3)	\$2.50 (\$1, \$5) USD/kg

2.2 Demand and supply functions

I assume that the demand functions for animal products exhibit constant elasticity of demand (CED), where the quantity demanded depends on the consumer prices of the good itself and its substitutes as the only variables. Likewise, I assume that the supply functions of these products exhibit constant elasticity of supply, where the quantity supplied depends only on the producer price of the good itself as a variable. This modelling approach has two main advantages. First, the functions are convex, making the CED model more realistic since demand for animal products is unlikely to drop to zero at high prices. Second, using constant elasticities allows for a convenient application of elasticity estimates from the economic literature.

2.2.1 Demand function

Let $Q_{d,i}$ be the quantity demanded in kg of any animal product i. It can be expressed in a CED function and depends on its own consumer price $P_{c,i}$ and the consumer prices of all J substitute goods with prices $P_{c,j}$. The parameter ε_i describes how $Q_{d,i}$ responds to changes in the consumer price of the good itself, and therefore is the constant own-price elasticity of demand (see Appendix A for proof). For normal goods, ε_i is negative because higher prices lead to lower demand. The parameter σ_{ij} describes how $Q_{d,i}$ responds to changes in the consumer price of good j, and therefore is the constant cross-price elasticity of demand (see Appendix B for proof). $L_{d,i}$ represents a scaling parameter that captures all the factors that determine $Q_{d,i}$ other than the product price and substitute prices, such as consumer preferences, and is assumed to be exogenous.

$$Q_{d,i} = L_{d,i} \times {P_{c,i}}^{\varepsilon_i} \times \underbrace{\prod_{j \neq i}^{J} P_{c,j}^{\sigma_{ij}}}_{\substack{substitute \\ prices}} \qquad (2.2)$$

2.2.2 Supply function

I assume that the quantity supplied of an animal product depends on the producer price of the product itself, but not the prices of substitute products. While it would be interesting to account for livestock producers switching the species of farmed animal, data on the cross-price elasticity of supply are lacking. Therefore, including this in the model would reduce its usefulness for forecasting the effects of a tax.

Let $Q_{s,i}$ be the quantity supplied of good i measured in kg. Let $P_{p,i}$ be the producer price of the same good. The parameter η_i describes how $Q_{s,i}$ responds to changes in the price of good i, and therefore is the own-price elasticity of supply (see Appendix C for proof). $L_{s,i}$ is a scaling parameter that captures factors determining $Q_{s,i}$ other than the product price, such as input prices and technological efficiency. These factors, which are assumed to be exogenous, determine the minimum price at which a farm can produce a given quantity of products.

$$Q_{s,i} = L_{s,i} \times P_{p,i}^{\eta_i} \tag{2.3}$$

The own-price elasticity of supply η_i can theoretically be either negative or positive. A negative elasticity can be the result of economies of scale due to, for example, automated feeding and specialisation of the labour force. Larger industries can supply the market at lower prices. A positive elasticity of supply can result from diminishing returns to scale. Companies may find it costly to find space or feed for more animals or are nearing the limits of the environment or environmental regulations. It can also be the result of supplier heterogeneity, where higher prices cause less efficient firms to enter the market. In the literature, elasticity of supply estimates for animal products are positive (Dey et al., 2007; Marsh, 1994; Muth et al., 2006, 2007).

2.2.3 Solving for the scaling parameter

As the values of the equilibrium prices P^*, equilibrium quantities Q^*, own-price elasticities of demand ε, cross-price elasticities σ, and price elasticities of supply η are generally known, we can know the values of all parameters in Equations 2.2 and 2.3 by substituting these data into the equations and solving for L.[3] These values for L are needed later in the method to calculate new equilibrium quantities and prices numerically. Here, we assume for simplicity that there are no taxes, such that the price that producers receive is exactly equal to the price that consumers pay.[4] Mathematically, this can be denoted as $P^*_{c,i,0} = P^*_{p,i,0}$ where the subscript 0 denotes the pre-tax situation.

Solving the demand function for $L_{d,i}$ provides us with a value of $L_{d,i}$:

$$L_{d,i} = \frac{Q^*_{d,i,0}}{\left(P^*_{c,i,0}\right)^{\varepsilon_i} \times \prod_{j \neq i}^{J} \left(P^*_{c,j,0}\right)^{\sigma_{ij}}} \tag{2.4}$$

Similarly, we can find the value of $L_{s,i}$ by solving the supply function for $L_{s,i}$:

$$L_{s,i} = \frac{Q^*_{s,i,0}}{\left(P^*_{p,i,0}\right)^{\eta_i}} \tag{2.5}$$

Calculated values for L are in Table 2.

[3] To solve for $L_{d,i}$ and $L_{s,i}$, simply divide both sides of the equation by the (cross-)price components of the function.
[4] This assumption is further discussed in Section 2.6.

2.3 Post-tax equilibria

The price consumers pay for a good ($P_{c,i}$) consists of the tax (τ_i) as defined in Section 2.1, plus the price that producers will receive ($P_{p,i}$). Producers receive the consumer price minus the tax. Therefore, we can set up the following equation:

$$P_{p,i} = P_{c,i} - \tau_i \tag{2.6}$$

In equilibrium, supply and demand quantities are equal. To find the new equilibrium consumer prices, we can thus set $Q^*_{d,i,1} = Q^*_{s,i,1}$ and substituting Equation 2.6 into the supply function. Let $P^*_{c,i,1}$ be the post-tax equilibrium consumer price and $P^*_{c,j,1}$ the post-tax equilibrium price of a substitute product. Subscript 1 denotes the post-tax situation.

$$\underbrace{L_{d,i} \times \left(P^*_{c,i,1}\right)^{\varepsilon_i} \times \prod_{j \neq i}^{J} \left(P^*_{c,j,1}\right)^{\sigma_{ij}}}_{Q^*_{d,i,1}} = \underbrace{L_{s,i} \times \left(P^*_{c,i,1} - \tau_i\right)^{\eta_i}}_{Q^*_{s,i,1}} \tag{2.7}$$

Equation 2.7 lacks a straightforward analytical solution, as raising the terms $P^*_{c,i,1}$ and $(P^*_{c,i,1} - \tau_i)$ to different exponents, ε_i and η_i, prevents algebraic isolation of the price variable. Moreover, because all products i are substitutes for each other, the interdependence of prices results in a complex system of non-linear equations without an analytical solution. However, since the values of all parameters are known, we can solve this non-linear system of equations for all values of $P_{c,i,1}$ simultaneously numerically using the Newton-Raphson method. This iterative root-finding algorithm can be used to produce successively more accurate approximations of the values for $P_{c,i,1}$ that satisfy Equation 2.7 based on an initial guess. For this purpose, I developed an R script using the `nleqslv` package (Hasselman, 2023).[5] I used $P^*_{p,i} + \tau_i$ as the initial guesses for the algorithm, as they can be expected to be close to the post-tax consumer price level.

With the post-tax equilibrium prices known, we can now find the new equilibrium quantity by plugging the new equilibrium consumer prices into the demand function. Let $Q^*_{i,1}$ be the post-tax equilibrium quantity.

$$Q^*_{i,1} = L_{d,i} \times \left(P^*_{c,i,1}\right)^{\varepsilon_i} \times \underbrace{\prod_{j \neq i}^{J} \left(P^*_{c,j,1}\right)^{\sigma_{ij}}}_{\substack{substitute \\ prices}} \tag{2.8}$$

2.4 Change in carbon emissions

Let ΔE_i be the absolute change in GHG emissions in kg CO_2-eq. of all consumption of product i per capita per year following the introduction of the tax. We can find this value by subtracting the GHG emissions in the original equilibrium from the expected GHG emissions in the post-tax equilibrium. GHG emissions are assumed to be proportional to the consumption of a given animal product. As defined in Section 3.2, CI_i is the CO_2-eq. GHG emissions per kg of edible food product in kg of product i.

$$\Delta E_i = CI_i\left(Q^*_{i,1} - Q^*_{i,0}\right) \tag{2.9}$$

[5] The script is available in the supplementary data package.

By summing over all values of i, we find the total absolute change in GHG emissions per capita per year as the result of the tax.

$$\Delta E = \sum_{i=1}^{I} \Delta E_i \tag{2.10}$$

2.5 Change in animal welfare

The absolute difference in animal welfare impacts of one product group per capita per year is calculated by replacing the carbon intensity CI_i with the animal intensity AI_i.

$$\Delta A_i = AI_i\left(Q_{i,1}^* - Q_{i,0}^*\right) \tag{2.11}$$

By summing over all values of i, we find the total absolute change in animal welfare impacts as the result of the tax per capita per year.

$$\Delta A = \sum_{i=1}^{I} \Delta A_i \tag{2.12}$$

The unit of AI_i can be the number of animal deaths (direct and total) and the duration of animal suffering (direct and total). Animal welfare indicators are assumed to be proportional to the consumption of a given animal product. This is discussed in more detail in Section 3.1.

2.6 Tax revenue

The tax revenue for one single taxed product i per capita per year can be calculated as the tax paid per product sold (τ_i) multiplied by the number of products sold ($Q_{i,1}^*$).

$$TR_i = \underbrace{\tau_i}_{P-axis} \times \underbrace{Q_{i,1}^*}_{Q-axis} \tag{2.13}$$

To find the total tax revenue over all products I being considered in the model, one can simply sum the tax revenues across all products.

$$TR = \sum_{i=1}^{I} TR_i \tag{2.14}$$

The calculations above assume that carbon, slaughter, and meat taxation do not interfere with other taxes, such as sales tax. In the U.S., most counties do not have a sales tax on groceries (USDA, 2021). The goal of the tax revenue calculation is not to predict the additional tax revenue for the treasury, but to compare the effects and trade-offs between carbon and slaughter taxation at equal tax revenue levels, as discussed in Section 2.7.

2.7 Threshold values for the Social Cost of Animal Use

Similar to how the Social Cost of Carbon (SCC) provides a monetary value of the badness of carbon emissions, I use a Social Cost of Animal Use (SCAU) as a monetary value of the badness of using an animal for food.[6] Depending on the use case, the SCAU can either be measured as the social cost of an animal death, or the social cost of one day of animal suffering in livestock farming or aquaculture. To allow for easier comparison to climate damages, the SCAU is expressed relative

[6] This study used SCAU instead of a "Social Cost of Suffering", because the animal welfare metrics do not measure suffering directly – rather, only its extensive margin.

to the SCC, such that an SCAU of 0.5 is equivalent to the social cost of ½ tonne of CO_2-eq. emissions in monetary terms.

Quantifying the SCAU relative to the SCC can help with answering two questions:

1. What is the threshold value for the SCAU at which a tax policy that reduces GHG emissions but increases animal suffering flips from being a net-external cost-reducing to a net-external cost-increasing policy?
2. What is the threshold value for the SCAU at which point a slaughter tax becomes more tax-efficient at reducing external cost than a carbon tax?

Let capital Θ_{SCAU} be the threshold value of SCAU relative to the SCC at which point a policy flips from being net-external cost reducing to net-external cost increasing. This threshold value exists for tax policies that reduce carbon emissions but increase animal suffering, or vice versa. This study measures the reduction of GHG emissions in kg CO_2-eq., but the SCC is typically measured in USD/tonne. Therefore, to get an SCAU threshold value relative to the SCC, we need to divide the threshold values by 1000 to get to the SCAU threshold relative to the SCC per tonne instead of per kg.

$$\Theta_{SCAU} = \begin{cases} \text{undefined} & \text{if } (\Delta A \times \Delta E \geq 0) \\ \dfrac{|\Delta E|}{|\Delta A|}/1000 & \text{otherwise} \end{cases} \tag{2.15}$$

For a carbon tax scenario where Θ_{SCAU} is undefined, this corresponds to the possible outcomes (a) and (b) from Section 1.2.1. This means that there is either a reduction in the consumption of all animal products, or an increase in the consumption of some animal products, but insufficient to cause an increase in the total number of individual animals consumed or the total days of suffering. Θ_{SCAU} is not undefined when carbon taxation would cause an increase in the total number of animals consumed (outcome c from Section 1.2.1). For slaughter taxation, Θ_{SCAU} is undefined when it causes a decrease in total greenhouse gas emissions, and not undefined when it causes an increase in total greenhouse gas emissions.

Let lowercase θ_{SCAU} be the threshold value at which slaughter taxation becomes more tax-efficient than carbon taxation at reducing total external costs, assuming their tax revenues TR are equal. Here, *tax efficiency* refers to the monetary external cost reduction per USD per capita per year. Just like in Equation 2.15, we divide by 1000 to get to the value relative to the SCC in tonnes of CO_2-eq.

$$\theta_{SCAU} = \frac{\Delta E_{carbontax} - \Delta E_{slaughtertax}}{\Delta A_{slaughtertax} - \Delta A_{carbontax}}/1000 \mid TR_{carbontax} \approx TR_{slaughtertax} \tag{2.16}$$

For the same reason that there is no analytical solution for $P^*_{c,i,1}$ in Equation 2.7, there exists no analytical solution for θ_{SCAU} given a value of TR, as it first requires solving the same system of equations. To compare the carbon tax and slaughter tax at equal tax revenues, I calculated consumer price equilibria $P^*_{c,i,1}$ and their corresponding values of TR, ΔE and ΔA in R for small increments in the tax levels C_e and C_k using the Newton-Raphson method described in Section 2.3.[7] The calculated values of TR and the corresponding values for tax levels C_e and C_k

[7] For carbon taxation: increments of 0.01 up to C_e = 30, and then increments of 0.1 up to C_e = 150. For slaughter taxation: increments of 0.001 up to C_k = 3, and then increments of 0.01 up to C_k = 30. θ_{SCAU} is most sensitive to absolute changes in the tax at lower levels. Higher increments at higher tax values were chosen for faster calculation.

and change in externalities ΔE and ΔA were then matched to the closest corresponding values of TR in the set $TR = \{10, 20, 30, \ldots, 240, 250\}$. This allows us to calculate θ_{SCAU} with approximately equal tax revenues as specified in Equation 2.16.

Both threshold values can be intuitively understood as the answer to the question: "How many CO_2-eq. emissions (in tonnes) are equally bad to one animal welfare impact, such as one animal death, or an animal spending one day in animal agriculture or aquaculture?".[8] For θ_{SCAU}, A is always operationalised as the amount of CO_2-eq. emissions equal to one direct animal death. For Θ_{SCAU}, the animal welfare indicator being compared against the SCC is specified in the accompanying text and using a subscript.

3. Data

3.1 Animal welfare impacts

I quantify the extensive margin of animal suffering through measures of animal deaths and the duration of suffering. Animal welfare research organisation Faunalytics (2022) provides data on these indicators for welfare-oriented institutional purchasers. However, Faunalytics' analysis includes how purchasing decisions cause a shift of the demand curve and along the supply curve. This partially offsets the initial reduction. In contrast, taxation causes an initial movement along the demand curve and causes a shift only through product substitution. This requires data on average impact per kg, rather than marginal impacts from purchasing decisions. I calculated these data by removing the elasticity adjustment from Faunalytics' calculations.[9] The measures for animal welfare impact used in Faunalytics (2022) are:

1. **Direct lives per kg.** The number of animals slaughtered to produce 1 kg of food. This includes the loss proportion between primary production and retail.
2. **Total lives per kg.** Identical to direct lives per kg, but also includes pre-production mortality, male chicks and calves being killed, and feed fish deaths.
3. **Direct days of suffering per kg.** The days an animal is alive to produce 1 kg of food. It is a product of the direct lives per kg and the average lifespan of the relevant species.
4. **Total days of suffering per kg.** Identical to direct days of suffering per kg, but also includes the duration of suffering of animals dying pre-production, male chicks and calves killed after birth, and feed fish. Feed fish are generally wild-caught and therefore assumed to suffer for one day.

Suffering is equally weighted for all species due to limited data on suffering intensity, sentience and pain receptivity.

3.2 Greenhouse gas emissions

I use Poore and Nemecek (2018) for data on GHG emissions per kg of food product. This dataset includes emissions from land use change, the farm, animal feed, processing, transport, retail, packaging, and food losses. Although Faunalytics (2022) categorises beef as a single group, Poore and Nemecek (2018) differentiate between beef sourced from beef herds and from dairy herds. To obtain a single metric for beef, a weighted average of these two points was calculated using data on the proportion (22.7%) of beef derived from dairy herds in the U.S. (Geiser & Boetel, 2017).

[8] Depending on the animal welfare indicator being discussed.
[9] The spreadsheet with calculations is available in the supplementary data package.

3.3 Quantities consumed

Data on per capita consumption of beef, chicken, and pork are from the U.S. Department of Agriculture (USDA, 2024a) and converted to kg. Fish consumption data from the USDA could not be directly used in this analysis because the available data on climate and animal welfare impacts only cover farmed fish, whereas wild-caught fish do not spend time in aquaculture. To estimate the quantity of farmed fish consumed in the U.S. by weight, I used Animal Charity Evaluators' estimate of the number of individual farmed fish consumed, and multiplied it by the average weight of a farmed fish (Smith, 2017).[10] This estimate includes per capita consumption of salmon, tilapia, pangasius, and catfish, which are the most commonly consumed farmed fish in the U.S.

3.4 Price data

Data on pre-tax prices in the U.S. are from the Meat Price Index on feedr.co (feedr, 2024) and converted from pound sterling to USD at June 2024 values.[11] While data on meat prices are also directly available from the USDA (2024b), these data do not include fish prices, and obtaining the data from a different source would lead to less comparable estimates.

3.5 Price elasticities of demand

For the own-price and cross-price elasticities of demand for meat products, I used the U.S. data from a meta-analysis evaluating 444 studies (Bouyssou et al., 2024). This paper is the source for the own-price elasticities of demand for all products and the cross-price elasticity of demand between all meat products. This paper does not include cross-price elasticities between meat products and fish. To fill this gap, I retrieved these data for the U.S. from Rahman et al. (2019), which relies on fewer observations than Bouyssou et al. (2024) but finds significant ($p<0.05$) estimates for cross-price elasticities of demand between meat and fish based on monthly per capita consumption expenditure data on animal proteins and their prices between 1995 and 2016 (Rahman et al., 2019). To make the data compatible with the existing categories of animal products, I used the estimates of beef and veal for beef only, of poultry for chicken only, and of fish and seafood for farmed finfish only.

Other meta-research has identified less elastic estimates for the own-price elasticity of demand for animal products. Andreyeva et al.'s (2010) preferred price elasticity estimates range from -0.75 for beef to -0.50 for fish. I check for robustness to elastic demand in Section 4.5.2.

3.6 Price elasticities of supply

Data on the price elasticities of demand are typically more readily available than the price elasticities of supply. Recent estimates of the price elasticity of supply were not always available for the U.S. The calibration therefore relies on estimates for other countries or on older estimates.

I used a U.S. estimate for the elasticity of supply for beef for an eighteen-month increase in supply following a 1% price increase from Marsh (1994). However, this research is quite old and farm dynamics may since have changed. For chicken and pork, I used estimates from the Research Triangle Institute commissioned by the USDA to understand the effects of regulation (Muth et al., 2006, 2007). The used estimate for the elasticity of farmed fish concerns data for South and South-East Asia (Dey et al., 2007), of which I took the average to function as a placeholder estimate for the U.S. The elasticities of supply differ substantially from each other.

All price elasticities of supply in the literature are positive, indicating diminishing returns. Chicken has a less elastic elasticity estimate, which suggests that producers already operate near

[10] Replicating results from Smith (2018) may yield slightly different results because the source runs a Monte-Carlo simulation when loaded.

[11] 1.2702 USD/GBP

maximum capacity to meet constant high demand. The robustness checks in Section 4.5 also calibrate the model assuming perfect elasticity of supply. The values for the calibration input data and the calculated values for scaling parameter L can be found in Table 2.

Table 2. *Model input data.*

i	prod.	*CI*	*AI*				P_0	Q_0	ε	η	σ				L_d	L_s
			deaths		**days**						**beef**	**chicken**	**pork**	**f. fish**		
			dir.	**total**	**dir.**	**total**										
		CO_2-eq./kg	deaths/kg		days/kg		$/kg	kg/capita/year								
1	beef	84.5	0.005	0.006	5.79	5.94	7.39	25.3	-0.92	0.61	–	0.13	0.11	0.03	94.01	7.53
2	chicken	9.9	0.929	1.072	45.52	46.34	4.58	30.9	-0.98	0.22	0.10	–	0.10	0.07	93.53	5.14
3	pork	12.3	0.021	0.834	3.48	4.45	9.03	22.1	-0.96	0.66	0.11	0.08	–	0.11	73.97	21.95
4	f. fish	13.6	0.602	5.954	196.22	215.59	18.48	5.2	-1.05	0.71	0.08	0.12	0.20	–	51.56	0.66

Note: prod. means product. i is the unique ID of a product. f. fish stands for farmed fish. CI are the associated emissions per kg of food product in kg CO_2-eq. emissions. AI are the associated animal welfare impacts per kg, expressed in the number of deaths or days in animal agriculture. P_0 is the pre-tax equilibrium price in USD per kg. Q_0 is the pre-tax equilibrium quantity in kg per capita per year. ε is the own-price elasticity of demand. η is the own-price elasticity of supply. σ is the cross-price elasticity of demand. L_d and L_s are calculated scaling parameters for demand and supply, respectively. Numbers are rounded. An unrounded data file is available in the supplementary information.

4. Results

The main calibration does not predict an increase in carbon emissions or animal welfare impacts for the carbon tax, slaughter tax, and meat and fish tax. Hence, there are no values for Θ_{SCAU} for the main calibrated model.

4.1 Scenario 1: Carbon tax

Despite concerns over the *Small Animal Replacement Problem*, the calibrated model predicts that carbon taxation decreases consumption of all animal products considered, albeit a much larger reduction for beef than for other animal products. This implies that a carbon tax decreases animal suffering on the extensive margin.

Table 3 presents the effects of the main scenario, which is a $25 USD tax per tonne of CO_2-eq. GHG emissions. The increase in price and reduction of consumption is most pronounced for beef because of its GHG-intensive supply chain. The change in consumption of other animal products is still negative, but much less economically significant. The reduction in GHG emissions resulting from this policy is 98% attributable to the reduction in beef consumption. The animal welfare effect of the policy is small. There are reductions in all indicators for animal suffering on the extensive margin, but none of those effects have a magnitude larger than -1.0%.

Table 3. *Effects of a $25 tax per tonne of CO_2-eq. GHG emissions (per capita per year)*

		Beef	**Chicken**	**Pork**	**F. fish**	**Total**
Economic effects	Tax (USD/kg)	$2.11	$0.25	$0.31	$0.34	
	Δ Consumer price (USD/kg)	$0.94 (12.8%)	$0.11 (2.3%)	$0.22 (2.5%)	$0.32 (1.7%)	
	Δ Producer price (USD/kg)	-$1.17 (-15.8%)	-$0.14 (-3.1%)	-$0.09 (-1.0%)	-$0.02 (-0.1%)	
	Δ Consumption (kg)	-2.505 (-9.9%)	-0.214 (-0.7%)	-0.139 (-0.6%)	-0.005 (-0.1%)	-2.863 (-3.4%)
	Tax revenue (USD)	$48.12	$7.56	$6.75	$1.77	$64.21
Climate effect	Δ Emissions (kg CO_2-eq.)	-211.582	-2.110	-1.716	-0.062	-215.470 (-7.7%)
Animal welfare effects	Δ Direct deaths	-0.013	-0.199	-0.003	-0.003	-0.217 (-0.7%)
	Δ Total deaths	-0.014	-0.229	-0.116	-0.027	-0.387 (-0.5%)
	Δ Direct time of suffering (days)	-14.504	-9.732	-0.485	-0.894	-25.615 (-1.0%)
	Δ Total time of suffering (days)	-14.892	-9.907	-0.621	-0.982	-26.403 (-0.9%)

Note: F. fish means farmed fish. Δ means absolute change. Percentage values are in brackets.

Because of the nonlinearity of the supply and demand functions, I tested two other tax levels ($10 and $50 USD/kg CO_2-eq., Appendix D) to account for potential sensitivity to the tax level. These calibrations resulted in predictions with a lower and higher magnitude, respectively, but did not change the qualitative results.

4.2 Scenario 2: Slaughter tax

The calibrated model predicts that slaughter taxation causes a reduction in greenhouse gas emissions, despite an increase in beef and pork consumption. This result is intuitive because the tax on beef and pork is much smaller than the tax on chicken and farmed fish, which causes the substitution effect to be larger than the direct effect of the tax. Unsurprisingly, the slaughter tax is much more effective at reducing the number of animal deaths and days of animal suffering than at reducing emissions. Under the main calibration ($2.50 per slaughtered animal, Table 4), the relative reduction in direct animal deaths is more than 13 times higher than the relative reduction in carbon emissions.

Table 4. *Effects of a $2.50 tax per animal slaughtered, including fish (per capita per year)*

		Beef	Chicken	Pork	F. fish	Total
Economic effects	Tax (USD/kg)	$0.01	$2.32	$0.05	$1.50	
	Δ Consumer price (USD/kg)	$0.09 (1.2%)	$0.56 (12.3%)	$0.11 (1.2%)	$0.80 (4.3%)	
	Δ Producer price (USD/kg)	$0.08 (1.1%)	-$1.76 (-38.4%)	$0.06 (0.6%)	-$0.71 (-3.8%)	
	Δ Consumption (kg)	0.161 (0.6%)	-3.171 (-10.3%)	0.089 (0.4%)	-0.141 (-2.7%)	-3.061 (-3.7%)
	Tax revenue (USD)	$0.34	$64.33	$1.15	$7.61	$73.42
Climate effect	Δ Emissions (kg CO_2-eq.)	13.633	-31.296	1.100	-1.926	-18.490 (-0.7%)
Animal welfare effects	Δ Direct deaths	0.001	-2.946	0.002	-0.085	-3.028 (-9.3%)
	Δ Total deaths	0.001	-3.400	0.075	-0.842	-4.166 (-5.0%)
	Δ Direct time of suffering (days)	0.935	-144.341	0.311	-27.734	-170.829 (-6.5%)
	Δ Total time of suffering (days)	0.960	-146.936	0.398	-30.472	-176.050 (-6.3%)

Note: F. fish means farmed fish. Δ means absolute change. Percentage values are in brackets.

At lower and higher levels of taxation ($1 per animal and $5 per animal, Appendix D), the magnitude of the effect is different, but the qualitative results remain the same.

4.3 Trade-offs between carbon and slaughter taxation

Whether carbon taxation or slaughter taxation is more tax-efficient[12] at reducing external costs depends on the value that a social planner or policymaker places on animal suffering relative to GHG emissions. As discussed in Section 2.7, the threshold value of the SCAU represents the relative valuation at which a slaughter tax becomes more tax-efficient at reducing external costs than a carbon tax. I compare policies at equal tax revenues because at this point only the external costs matter to a policymaker. The threshold value depends on the tax revenue because of differences in elasticities and the non-linearity of supply and demand.

Figure 2 shows the relationship between the threshold value of the SCAU and tax revenue. At lower tax revenues, the threshold value is decreasing in tax revenue, but this dynamic reverses after tax revenues exceed approximately $210 USD per capita per year. The data show that a slaughter tax is a more tax-efficient policy measure to reduce external costs as long as the SCAU is more than 10% of the SCC. In other words, a social planner should prefer slaughter taxation over carbon taxation when avoiding the death of one animal is seen as more important than avoiding 100 kg of CO_2-eq. GHGs emissions. At higher levels of taxation, this threshold is as low as 4% of the SCC or emitting 40 kg of CO_2-eq. GHGs.

[12] As defined in Section 2.7, *tax-efficiency* refers to the monetary external cost reduction per USD per capita per year.

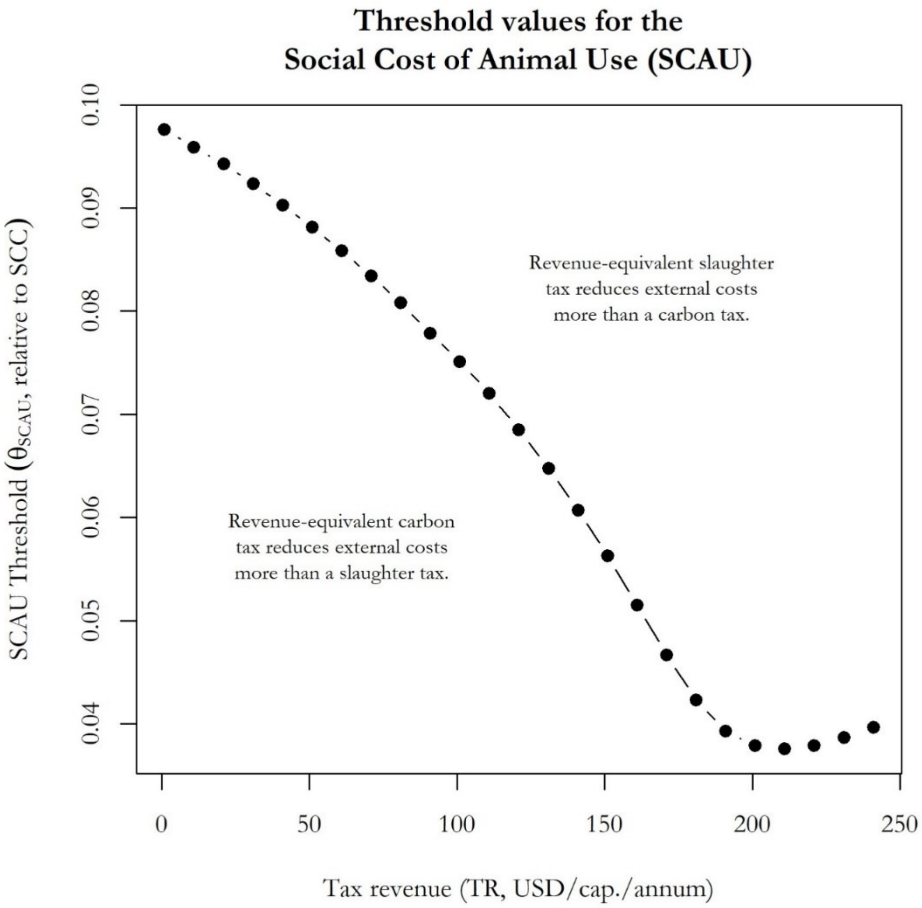

Figure 2. *Threshold values for the Social Cost of Animal Use for different tax revenues*

Assuming that the SCC is $185 USD per tonne of CO_2-eq. GHG emissions following Rennert et al. (2022), the threshold value for the SCAU ranges somewhere between $17.48 USD (at low tax revenues) and $7.00 USD (at high tax revenues). Table 5 presents the values of the SCAU threshold at an SCC of $185 USD at different tax revenues with corresponding carbon and slaughter tax levels.

Table 5. *Threshold values for the Social Cost of Animal Use for different tax revenues, including associated tax levels*

Tax revenue (USD/ cap./year)	**Associated carbon tax** (USD/tonne CO_2-eq.)	**Associated slaughter tax** (USD/animal killed)	$\boldsymbol{\theta_{SCAU}}$ (Relative to SCC)	$\boldsymbol{\theta_{SCAU} \vert SCC = 185}$ (USD/animal killed)
$0	$0.00	$0.00	n/a	–
$20	$7.36	$0.63	0.0945	$17.48
$40	$15.08	$1.29	0.0904	$16.73
$60	$23.23	$2.00	0.0860	$15.92
$80	$31.90	$2.76	0.0812	$15.02
$100	$41.00	$3.60	0.0752	$13.92
$120	$50.80	$4.56	0.0688	$12.72
$140	$61.30	$5.74	0.0611	$11.30
$160	$72.60	$7.39	0.0520	$9.62
$180	$84.90	$10.24	0.0426	$7.89
$200	$98.30	$14.89	0.0380	$7.02
$220	$112.80	$20.67	0.0378	$7.00
$240	$128.70	$27.28	0.0395	$7.31

4.4 Scenario 3: Meat and fish tax

A meat and fish tax can be seen as a second-best alternative to taxing climate impacts and animal slaughter directly by promoting a reduction in meat and fish consumption regardless of the specific product. As visible in Table 6, the meat and fish tax causes reductions in the weight-units consumption of meat and fish, total carbon emissions, and the number of farmed animals. Reductions in carbon emissions are mostly due to reductions in beef (79%), and over half of the reductions in the animal welfare indicators are attributable to reductions in chicken consumption.

Table 6. *Effects of a $2.50 tax per kg meat or fish (per capita per year)*

		Beef	**Chicken**	**Pork**	**F. fish**	**Total**
Economic effects	Tax (USD/kg)	$2.50	$2.50	$2.50	$2.50	
	Δ Consumer price (USD/kg)	$1.28 (17.3%)	$0.73 (15.9%)	$1.32 (14.7%)	$1.65 (8.9%)	
	Δ Producer price (USD/kg)	-$1.22 (-16.6%)	-$1.77 (-38.6%)	-$1.18 (-13.0%)	-$0.85 (-4.6%)	
	Δ Consumption (kg)	-2.628 (-10.4%)	-3.196 (-10.4%)	-1.948 (-8.8%)	-0.170 (-3.3%)	-7.942 (-9.5%)
	Tax revenue (USD)	$56.67	$69.18	$50.31	$12.57	$188.73
Climate effect	Δ Emissions (kg CO_2-eq.)	-221.977	-31.548	-23.980	-2.313	-279.818 (-10.1%)
Animal welfare effects	Δ Direct deaths	-0.014	-2.969	-0.040	-0.102	-3.126 (-9.6%)
	Δ Total deaths	-0.015	-3.428	-1.624	-1.010	-6.077 (-7.4%)
	Δ Direct time of suffering (days)	-15.217	-145.504	-6.774	-33.297	-200.792 (-7.6%)
	Δ Total time of suffering (days)	-15.624	-148.120	-8.677	-36.585	-209.005 (-7.5%)

Note: F. fish means farmed fish. Δ means absolute change. Percentage values are in brackets.

At meat taxation of $1 or $5 USD (Appendix D) per kg meat or fish, only the magnitude of the effect changes, but the overall signs remained the same.

4.5 Robustness checks and alternative calibrations

The calibrated model depends on estimates of elasticities from the economic literature, which may not be perfectly internally or externally valid. Moreover, policymakers may decide to only apply a tax to some animal products, and not to others. To ensure the reliability and consistency of the model's findings, I perform four robustness checks of the results under different assumptions.

The robustness checks confirm the reliability of the main findings across varied assumptions, with consistent qualitative outcomes. Notable deviations include modest increases in animal suffering under higher cross-price elasticities and greater reductions in emissions with perfect supply elasticity. Exempting fish from taxation slightly increases farmed fish consumption but does not significantly alter the main results.

4.5.1 Doubled cross-price elasticities of demand

Higher cross-price elasticities increase substitution between products, making it more likely that a slaughter or carbon tax increases the externality that it is not targeting. After implementation, the cross-price elasticities may go up when consumers become more familiar with ways to substitute one animal product with another.

To test the robustness of the qualitative results to higher values of σ, I re-calibrated the model with double cross-price elasticities (Appendix E). In this calibration, carbon taxation of $10, $25, and $50 USD/tonne CO_2-eq. causes a modest increase in the total deaths indicator. For a $25 USD carbon tax, the model now predicts a 0.39% increase in total animal deaths because of increased pork and farmed fish consumption, but still a reduction in the other animal welfare indicators. The threshold for the SCAU at which this policy increases external costs is when one animal death becomes more important than a reduction of 0.61 tonnes of CO_2-eq. GHG emissions ($\Theta_{SCAU,total\ deaths} \approx 0.61$).

Slaughter taxation of $1, $2.50, and $5 USD per animal results in a small increase in GHG emissions. For a slaughter tax of $2.5 USD, the model now predicts an increase in GHG emissions of 0.25%. This policy increases external costs when avoiding one direct animal death is less important than a reduction of 0.0024 tonnes of CO_2-eq. GHG emissions ($\Theta_{SCAU,direct\ deaths} \approx 0.0024$).

4.5.2 Less elastic demand

A meta-study by Andreyeva et al. (2010) found substantially less elastic values for the price elasticity of demand than the values from Bouyssou et al. (2024) used in the main calibration. Andreyeva et al. (2010) found values of -0.75 for beef, -0.68 for poultry, -0.72 for pork, and -0.5 for fish.

I re-calibrated the model using the own-price elasticities of demand by Andreyeva et al. (2010) but with the original cross-price elasticities of demand (Appendix F). The model now predicts a small increase in the consumption of farmed fish after carbon taxation of $10, $25, and $50 USD/tonne CO_2-eq. This increase is sufficient to cause a small increase in the number of total animal deaths, but not an increase in any of the other animal welfare indicators. At carbon taxation of $25 USD, the increase in farmed fish consumption is approximately 0.7%. The increase in total deaths is approximately 0.027%, which causes the carbon tax to become a net-negative policy when avoiding one total death becomes more important than avoiding 8.45 tonnes of CO_2-eq. ($\Theta_{SCAU,total\ deaths} \approx 8.45$).

4.5.3 Perfect elasticity of supply

Perfectly elastic supply describes a situation where any change in price leads to an infinite change in the quantity supplied ($\eta \to \infty$). In an inverse supply diagram, this is represented by a horizontal line, indicating that the price remains constant while the quantity supplied can vary infinitely. Although this represents an extreme case, it provides useful theoretical insights into how supply responsiveness behaves as elasticity increases. In the long term, supply can become more elastic when becomes easier to adjust inputs like capital and land, or as producers enter or exit markets. Modelling with perfect elasticity helps assess whether the qualitative outcomes of the analysis remain consistent and insightful across varying degrees of supply elasticity.

Methodologically, it is no longer necessary to use a root-finding algorithm like the Newton-Raphson method to solve for price values. The producer price is a constant, which means the full burden of the tax falls on consumers. Hence, the post-tax consumer price is the pre-tax equilibrium price plus the tax.

$$P^*_{c,i,1} = P^*_{i,0} + \tau_i \tag{4.1}$$

For carbon taxation, the qualitative results do not change for the tested tax levels of $10, $25, and $50 USD/tonne CO_2-eq (Appendix G). However, as expected, the magnitude of the effect of the tax is larger, as the full tax burden is on the consumers. For a $25 USD carbon tax, the reduction in emissions is more than twice as much (-15.3%) as predicted by the main calibrated model with an equal tax level (-7.7%). In contrast to Bruers (2024), the model does not predict an increase in the consumption of any animal product.

For slaughter taxation, the model now predicts an increase in the consumption of beef and pork under the tested tax levels of $1, $2.50, and $5 USD per slaughtered animal. These increases are sufficient to slightly increase the total amount of GHG emissions from animal products. At a slaughter tax of $2.5 USD, emissions are expected to rise by 1.0%. This specification increases external costs when reducing the amount of (direct) slaughtered animals by 1 is less important than avoiding 0.005 tonnes of CO_2-eq ($\Theta_{SCAU,direct\ deaths} \approx 0.005$).

Under perfect elasticity of supply, the SCAU threshold values at which taxation becomes more efficient in reducing external costs increase with tax revenue (Appendix G), unlike in the main specification. This is due to the greater price elasticity of supply for chicken compared to other products in the main model, where higher slaughter taxes were needed to reduce chicken consumption. Consequently, carbon taxes were more effective at reducing beef consumption than slaughter taxes were for chicken. With perfect elasticities, however, low-revenue slaughter taxes are more effective at reducing chicken consumption because even small excise taxes lead to significant relative price changes, driving down demand.

4.5.4 No taxation on fish products

In the main model calibration, taxation was applied to all animal products, including fish. However, fish is often culturally perceived as distinct from meat, which could lead policymakers to adopt a tax exempting fish. The tax exemption of farmed fish makes the product more attractive, which could increase animal deaths and duration of suffering.

To test whether exempting farmed fish from the results influences the qualitative results of this study, I calibrated the model with $\tau_{farmedfish} = 0$ (Appendix H). The tested levels of carbon taxation ($10, $25, and $50 USD/tonne CO_2-eq.) cause an increase in the consumption of farmed fish, but this is insufficient to increase the total number of animals slaughtered or the time of suffering. A carbon tax of $25 USD increases farmed fish consumption by approximately 0.7%, but the number of direct deaths is still reduced by 0.6%, as compared to 0.7% in the baseline specification. Therefore, the qualitative results for carbon taxes are robust against not taxing fish.

The tested levels of slaughter taxation ($1, $2.5, and $5 USD/slaughtered animal) now also cause an increase in the consumption of farmed fish, in addition to increases in beef and pork consumption. For none of these calibrations, this leads to an increase in total carbon emissions, animal deaths, or duration of suffering. At slaughter taxation of $2.5 USD per animal, the consumption of farmed fish goes up by 1.2%, as compared to -2.7% is the main calibration.

5. Discussion

5.1 Interpretation of results

This study highlights the inherent trade-offs between climate policies and animal welfare when addressing the externalities associated with meat consumption. The findings provide a nuanced understanding of how different tax structures – carbon, slaughter, and meat/fish taxes – impact both greenhouse gas emissions and animal suffering. That neither externality can be fully addressed in isolation without affecting the other, nor can a slaughter tax or carbon tax properly address the externality it is not designed for.

5.1.1 Tax scenarios

The *carbon tax* scenario sees a large reduction in greenhouse gas emissions, particularly driven by decreased beef consumption. However, the relatively modest impact on reducing animal suffering is notable. This suggests that while carbon taxation can be an effective tool for mitigating climate change, it is insufficient as a standalone measure for improving animal welfare outcomes. While a carbon tax does not cause a Small Animal Replacement Problem, its effect on animal welfare is limited. This implies that policymakers focused on holistic sustainability goals must consider other interventions to address animal welfare.

The *slaughter tax* presents a contrasting outcome, where substantial reductions in animal suffering are achieved primarily by decreasing chicken consumption. However, the relatively small impact on emissions, especially the slight increases in beef and pork consumption, highlights the challenge of addressing both externalities simultaneously. The findings suggest that while a slaughter tax is more effective at reducing suffering, it may require additional regulations or taxes to reduce the carbon emissions from the food system.

The *meat and fish tax* offers a more balanced approach, reducing both emissions and animal suffering in approximately equal amounts, albeit not as effectively as the targeted carbon or slaughter taxes in their respective areas of impact. The significance of this finding lies in its practicality. For policymakers who seek a simpler or more politically feasible solution, a general meat and fish tax could serve as a second-best option that moderately addresses both externalities without the need for combined slaughter and carbon taxation. However, the trade-off is that neither externality is addressed as aggressively as it would be with more targeted taxation.

5.1.2 Trade-offs and the Social Cost of Animal Use

By comparing the Social Cost of Animal Use (SCAU) to the Social Cost of Carbon (SCC), the model reveals that, depending on how society values animal welfare relative to climate impacts, a slaughter tax could be more tax-efficient than a carbon tax in reducing overall external costs. This introduces a critical policy consideration: if the welfare of animals is assigned a sufficiently high moral weight, slaughter taxes may become a more attractive policy tool than carbon taxation.

5.2 Limitations and future research

5.2.1 Quality of animal welfare indicators

The number of animals killed and the duration of their suffering serve as useful proxies to understand changes in animal welfare on the extensive margin. However, the dependent variables do not measure animal welfare perfectly, as it excludes the intensity of suffering.

The approach of this study relies on two assumptions about animal welfare. Firstly, it assumes that farmed animals have net-negative lives, i.e. total welfare increases with fewer animals. An increase in the number of slaughtered animals and the time that they spend in animal agriculture or aquaculture is considered an economic bad. Following a strictly utilitarian framework, if animals have net-positive lives, increasing the size of animal agriculture and aquaculture would be good for animal welfare, as the total quantity of animal welfare would increase. This makes whether animals have a "life worth living" an important question in animal welfare policy (Espinosa & Treich, 2021, 2024).

Secondly, the indicators assume that all farmed animals experience an equal amount of suffering throughout their lifetime (for the deaths-indicators) or per time unit lived (for the time-related indicators). However, farmed animals may have different quality of life, as some species may live in more stressful, painful, or restricted environments than others, on average. Additionally, the capacity to experience suffering may be different for different animals due to biological differences in, for example, sentience and sensitivity to pain.

Recent advances in welfare biology and charity research aim to quantitatively distinguish the suffering experienced by different species (Charity Entrepreneurship, 2024; Gaffney et al., 2023). Future economic research could differentiate in different degrees of suffering experienced by different animals. It may also test (hypothetical) models where the quality of life of some animals is considered net-positive and that of others net-negative.

5.2.2 Abatement in the supply chain

The carbon tax and slaughter tax evaluated in this study assume that carbon emissions and animal suffering per kg of food product are constant. In reality, a carbon tax creates incentives for producers to abate emissions in the supply chain. This reduces the tax and dampens its effect on consumption reduction and product substitution. A carbon tax can also affect animal welfare through other means, such as by breeding for increased yields and through agricultural intensification (Shields & Orme-Evans, 2015). Likewise, a slaughter tax incentivizes producers to have higher yields per animal, which reduces the tax and its effects. Future research should explicitly model abatement for a better understanding of intra-farm dynamics.

5.2.3 Consideration of other products

Beef, chicken, pork, and farmed fish account for the vast majority in the consumption of meat and fish in the U.S. (Smith, 2017; USDA, 2024a). However, some less-consumed animal products may still be relevant for the analysis. As visible in Figure 1, substitution from cheese to eggs and vice versa could invertedly increase externalities, and even small increases in shrimp consumption can change the qualitative results of the study. Future research could include other animal products to understand substitution to less-consumed animal products.

5.2.4 Possibility of incomplete carbon taxation

A government may, for ease of measurement or political acceptability, decide to only tax the emissions in one part of the supply chain of animal products. There are large differences in the relative importance of emissions from different stages in the supply chain of animal products (Poore & Nemecek, 2018). Incomplete taxation could change the relative tax incentives, which in turn affects changes in consumption and associated externalities. Likewise, the slaughter tax in this study only applies to animals directly slaughtered for food. If indirect deaths would be accounted for in the slaughter tax, this would more than quadruple the tax on pork and increase the tax on farmed fish nearly ten-fold, while the tax on beef and chicken would stay largely unaffected. Future research should consider simulations where only part of the emissions or animal welfare impacts in the supply chain are taxed to better understand how this could affect consumption patterns and externalities.

5.2.5 Other externalities

Future research may include additional external and undesirable effects of animal product consumption. Recent literature has attempted to develop the concept of a "social cost of meat" and an associated meat tax by considering environmental externalities, the learning curves for alternative protein technologies, adverse health effects, animal welfare, and distributional effects (Funke et al., 2022). Consultancy firm CE Delft has developed social costs per kg of meat that include the costs of GHG emissions, pollutants, land-use impacts, biodiversity loss, and livestock diseases (Odegard et al., 2020). By including environmental effects other than climate change, they arrive at recommended meat taxes with fewer relative differences than those based on GHG emissions alone. This would reduce substitution effects between animal products. Future research could develop models of taxation, product substitution, and multiple externalities that extend beyond climate change and animal suffering to include other environmental externalities, health effects, and distributional effects of meat taxation.

5.2.6 External validity

Future research may calibrate the model with data for different markets to understand the effects of carbon, slaughter, and meat taxation elsewhere. People in different countries may respond differently to price changes because of differences in spendable income or cultural preferences for specific types of meat, which could affect the predicted effects of this model.

6. Conclusions

As the climate impacts of the food system gain increasing public attention, policymakers are exploring carbon pricing schemes for food products to promote more sustainable diets. However, focusing solely on climate impacts overlooks the animal suffering associated with consuming animal products. A significant trade-off exists between carbon-intensive animal products that cause relatively few animal deaths (e.g., beef, pork) and products with lower emissions but higher animal death rates (e.g., chicken, farmed fish). This highlights the need to incorporate animal welfare considerations into policies targeting carbon emissions from food.

Although the model in this study did not predict that slaughter or carbon taxes would exacerbate the externality they do not target, the relative significance of carbon emissions versus animal suffering should guide policy preferences. Alternatively, policymakers could design meat and fish taxes that result in comparable reductions in both externalities.

This study contributes to the public and academic debate in three main ways. First, it emphasizes the importance of addressing the extensive margin of animal suffering (the number of animals and duration of suffering) in the ethical and policy discussions on climate change, beyond just the intensity of suffering. Second, it advances economic methodology by offering a model that accounts for tax-induced substitution effects between products, incorporating own-price and cross-price elasticities of demand as well as price elasticities of supply. This model can be adapted to other product categories with multiple externalities. Third, the study provides insights for policymakers on the implications of carbon taxes, slaughter taxes, and meat and fish taxes.

7. Supplementary data

All code, input data, and output tables used in this paper are available on GitHub.

https://github.com/SoemanoZeijlmans/MeatTaxSubstitution

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Glossary of Terms

Table 7. *Glossary of Terms*

Term	Definition
CED	Constant Elasticity of Demand
eq.	Equivalent
GHG	Greenhouse gas
kg	Kilogram
mec	Marginal external costs
Q.E.D.	Quod erat demonstrandum (end of proof)
SARP	Small Animal Replacement Problem
SCAU	Social Cost of Animal Use
SCC	Social Cost of Carbon
U.S.	United States
WTP	Willingness-to-pay

Table 8. *List of symbols*

Symbol	Unit	Definition
Δ	multiple	Absolute difference
τ	\$/kg	Excise tax
ε	unitless	Own-price elasticity of demand
σ	unitless	Cross-price elasticity of demand
η	unitless	Own-price elasticity of supply
CI	ton CO_2-eq/kg	Carbon intensity: greenhouse gases emitted per kg
AI	multiple	Animal intensity per kg (multiple definitions)
P	\$/kg	Price
Q	kg/capita/year	Quantity
L	unitless	Scaling parameter for demand and supply functions
C	\$/…	Price of carbon (per tonne CO_2-eq.), slaughter (per animal), or meat (per kg), depending on subscript.
TR	\$/capita/year	Tax revenue
A	count or days	Animal welfare impacts (animal deaths or days of suffering)
E	kg CO_2-eq.	Emissions in CO_2-eq.
θ	unitless	Threshold value for the SCAU relative to the SCC at which a slaughter tax becomes more tax-efficient at reducing external costs than a carbon tax
Θ	unitless	Threshold value for the SCAU relative to the SCC at which a policy becomes net-external cost increasing rather than reducing.
I	count	Number of animal products.
J	count	Number of substitute products.
Π	unitless	Placeholder for the product term in Appendix A
SCC	USD/tonne CO_2-eq.	Social Cost of Carbon
$SCAU$	USD/animal	Social Cost of Animal Use

Table 9. *List of subscripts*

Symbol	Definition
i	…of a given product
j	…of a given substitute product
$total$	…across all products in the model
s	…of supply
d	…of demand
p	…for producers
c	…for consumers
0	…in initial situation
1	…in post-tax situation
e	…per 1 tonne of CO_2-eq. emissions
k	…per animal slaughtered
m	…per kg of meat or fish

Table 10. *List of superscripts*

Symbol	Definition
$*$	…in equilibrium

Appendix A – Proof of constant own-price elasticity of demand

The specified demand function takes the following form:

$$Q_{d,i} = L_{d,i} \times P_{c,i}^{\varepsilon_i} \times \underbrace{\prod_{j \neq i}^{J} P_{c,j}^{\sigma_{ij}}}_{\substack{substitute \\ prices}} \tag{2.2}$$

where $Q_{d,i}$ is the quantity demanded of good i, which depends on scaling parameter $L_{D,i}$, the consumer price $P_{c,i}$, and the own-price elasticity of demand ε_i. It also depends on the consumer prices $P_{c,j}$ of J substitute goods, with corresponding cross-price elasticities σ_{ij}. The **objective** is to proof that the demand function in Equation 2.2 has a constant own-price elasticity of demand.

Definition of own-price elasticity of demand:

$$\text{elasticity}_i = \frac{dQ_{d,i}}{dP_{c,i}} \times \frac{P_{c,i}}{Q_{d,i}}$$

1. For simplicity, let Π_i be a placeholder for the product term containing the prices of substitutes J for product i. This is possible because the product term does not contain the own-price $P_{c,i}$. We can now express the demand function as:
$$Q_{d,i} = L_{d,i} \times P_{c,i}^{\varepsilon_i} \times \Pi_i$$
2. Differentiate the demand function with respect to $P_{c,i}$.
Using the power rule of differentiation, we find:
$$\frac{dQ_{d,i}}{dP_{c,i}} = L_{d,i} \times \varepsilon_i \times {P_{c,i}}^{\varepsilon_i - 1} \times \Pi_i$$
3. Substitute the derivative from Step 2 into the elasticity formula.
$$\text{elasticity}_i = L_{d,i} \times \varepsilon_i \times {P_i}^{\varepsilon_i - 1} \times \Pi_i \times \frac{P_{c,i}}{Q_{d,i}}$$
4. As $P_{c,i} \times P_{c,i}^{\varepsilon_i - 1} = P_{c,i}^{\varepsilon_i}$, this simplifies to:
$$\text{elasticity}_i = \frac{L_{d,i} \times \varepsilon_i \times P_{c,i}^{\varepsilon_i} \times \Pi_i}{Q_{d,i}}$$
5. Substitute the simplified demand function from Step 1 into the elasticity formula for $Q_{d,i}$.
$$\text{elasticity}_i = \frac{L_{d,i} \times \varepsilon_i \times P_{c,i}^{\varepsilon_i} \times \Pi_i}{L_{d,i} \times P_{c,i}^{\varepsilon_i} \times \Pi_i}$$
6. Cancelling out the common terms results in a constant elasticity:
$$\therefore \text{elasticity}_i = \varepsilon_i$$

Conclusion and implication

The demand function specified in Equation 2.2 exhibits constant own-price elasticity of demand. This means that elasticity estimates from economic literature can be applied to the specified demand function without adjusting for the equilibrium quantity or price.

Appendix B – Proof of constant cross-price elasticity of demand

The specified demand function takes the following form:

$$Q_{d,i} = L_{d,i} \times P_{c,i}^{\varepsilon_i} \times \underbrace{\prod_{j \neq i}^{J} P_{c,j}^{\sigma_{ij}}}_{\substack{substitute \\ prices}} \tag{2.2}$$

where $Q_{d,i}$ is the quantity demanded of good i, which depends on scaling parameter $L_{D,i}$, the consumer price $P_{c,i}$, and the own-price elasticity of demand ε_i. It also depends on the consumer prices $P_{c,j}$ of J substitute goods, with corresponding cross-price elasticities σ_{ij}. The **objective** is to proof that the demand function in Equation 2.2 has a constant cross-price elasticity of demand.

Definition of cross-price elasticity of demand:

$$\text{cross-price elasticity}_i = \frac{dQ_{d,i}}{dP_{c,j}} \times \frac{P_{c,j}}{Q_{d,i}}$$

1. Edit the expression by substituting the product term with a single substitute price $P_{c,j}$ with exponent σ_{ij}, as we are interested in the effect of one substitute at a time and can disregard the other substitutes.
$$Q_{d,i} = L_{d,i} \times P_{c,i}^{\varepsilon_i} \times P_{c,j}^{\sigma_{ij}}$$
2. Differentiate the demand function with respect to the consumer price of the substitute $P_{c,j}$. Using the power rule of differentiation, we find:
$$\frac{dQ_{S,i}}{dP_j} = L_{d,i} \times P_{c,i}^{\varepsilon_i} \times \sigma_{ij} \times P_{c,j}^{\sigma_{ij}-1}$$
3. Substitute the derivative from Step 2 into the elasticity formula.
$$\text{cross-price elasticity}_i = L_{d,i} \times {P_{c,i}}^{\varepsilon_i} \times \sigma_{ij} \times P_{c,j}^{\sigma_{ij}-1} \times \frac{P_{c,j}}{Q_{d,i}}$$
4. As $P_{c,j} \times P_{c,j}^{\sigma_{ij}-1} = P_{c,j}^{\sigma_{ij}}$, this simplifies to:
$$\text{cross-price elasticity}_i = \frac{L_{d,i} \times {P_i}^{\varepsilon_i} \times \sigma_{ij} \times P_j^{\sigma_{ij}}}{Q_{d,i}}$$
5. Substitute the edited demand function from Step 1 into the elasticity formula for $Q_{S,i}$.
$$\text{cross-price elasticity}_i = \frac{L_{d,i} \times {P_{c,i}}^{\varepsilon_i} \times \sigma_{ij} \times P_{c,j}^{\sigma_{ij}}}{L_{d,i} \times P_{c,i}^{\varepsilon_i} \times P_{c,j}^{\sigma_{ij}}}$$
6. Cancelling out the common terms results in a constant elasticity:
$$\therefore \text{cross-price elasticity}_i = \sigma_{ij}$$

Conclusion and implication

The demand function specified in Equation 2.2 exhibits constant cross-price elasticity of demand. This means that elasticity estimates from economic literature can be applied to the specified demand function without adjusting for the equilibrium quantity or price.

Appendix C – Proof of constant own-price elasticity of supply

The specified supply function takes the following form:

$$Q_{s,i} = L_{s,i} \times P_{p,i}^{\eta_i} \tag{2.3}$$

where $Q_{s,i}$ is the quantity supplied of good i, which depends on the scaling $L_{s,i}$, the producer price $P_{p,i}$, and the own-price elasticity of supply η_i. The **objective** is to proof that the specified supply function in Equation 2.3 has a constant own-price elasticity of supply.

Definition of price elasticity of supply:

$$\text{elasticity}_i = \frac{dQ_{s,i}}{dP_{p,i}} \times \frac{P_{p,i}}{Q_{s,i}}$$

1. Differentiate the supply function with respect to $P_{p,i}$.
   Using the power rule of differentiation, we find:
   $$\frac{dQ_{s,i}}{dP_{p,i}} = L_{s,i} \times \eta_i \times P_{p,i}^{\eta_i - 1}$$
2. Substitute the derivative from Step 1 into the elasticity formula.
   $$\text{elasticity}_i = L_{s,i} \times \eta_i \times P_{p,i}^{\eta_i - 1} \times \frac{P_{p,i}}{Q_{s,i}}$$
3. As $P_{p,i} \times P_{p,i}^{\eta_i - 1} = P_{p,i}^{\eta_i}$, this simplifies to:
   $$\text{elasticity}_i = \frac{L_{s,i} \times \eta_i \times P_{p,i}^{\eta_i}}{Q_{s,i}}$$
4. Substitute the supply function (Equation 2.3) into the elasticity formula.
   $$\text{elasticity}_i = \frac{L_{s,i} \times \eta_i \times P_{p,i}^{\eta_i}}{L_{s,i} \times P_{p,i}^{\eta_i}}$$
5. Cancelling out the common terms results in a constant elasticity:
   $$\therefore \text{elasticity}_i = \eta_i$$

Conclusion and implication

The supply function specified in Equation 2.3 exhibits constant own-price elasticity of supply. This means that elasticity estimates from economic literature can be applied to the specified supply function without adjusting for the equilibrium quantity or price.

Appendix D – Results tables for alternative tax levels

This appendix presents the results of the main calibration for different tax levels not presented in the main tax. The results of tax levels provided in this appendix are as follows:

- Carbon tax
    - 10 USD/tonne CO_2-eq.
    - 50 USD/tonne CO_2-eq.
- Slaughter tax
    - 1 USD/slaughtered animal
    - 5 USD/slaughtered animal
- Meat tax
    - 1 USD/kg
    - 5 USD/kg

Since none of the tax levels evaluated in this appendix increased an externality, Θ_{SCAU} values are not reported because they are not applicable in any case.

Table 11. *Effects of a \$10 tax per tonne of CO_2-eq. GHG emissions (per capita per year)*

		Beef	**Chicken**	**Pork**	**F. fish**	**Total**
Economic effects	Tax (USD/kg)	$0.84	$0.10	$0.12	$0.14	
	Δ Consumer price (USD/kg)	$0.36 (4.9%)	$0.04 (0.9%)	$0.09 (1.0%)	$0.13 (0.7%)	
	Δ Producer price (USD/kg)	-$0.49 (-6.6%)	-$0.06 (-1.2%)	-$0.04 (-0.4%)	-$0.01 (-0.1%)	
	Δ Consumption (kg)	-1.020 (-4.0%)	-0.086 (-0.3%)	-0.057 (-0.3%)	-0.002 (0.0%)	-1.165 (-1.4%)
	Tax revenue (USD)	$20.50	$3.04	$2.71	$0.71	$26.96
Climate effect	Δ Emissions (kg CO_2-eq.)	-86.189	-0.847	-0.702	-0.028	-87.765 (-3.2%)
Animal welfare effects	Δ Direct deaths	-0.005	-0.080	-0.001	-0.001	-0.087 (-0.3%)
	Δ Total deaths	-0.006	-0.092	-0.048	-0.012	-0.157 (-0.2%)
	Δ Direct time of suffering (days)	-5.908	-3.905	-0.198	-0.397	-10.408 (-0.4%)
	Δ Total time of suffering (days)	-6.066	-3.975	-0.254	-0.436	-10.732 (-0.4%)

Note: F. fish means farmed fish. Δ means absolute change. Percentage values are in brackets.

Table 12. *Effects of a \$50 tax per tonne of CO_2-eq. GHG emissions (per capita per year)*

		Beef	Chicken	Pork	F. fish	Total
Economic effects	Tax (USD/kg)	\$4.22	\$0.49	\$0.62	\$0.68	
	Δ Consumer price (USD/kg)	\$2.04 (27.6%)	\$0.22 (4.7%)	\$0.45 (5.0%)	\$0.64 (3.5%)	
	Δ Producer price (USD/kg)	-\$2.18 (-29.5%)	-\$0.28 (-6.0%)	-\$0.17 (-1.8%)	-\$0.04 (-0.2%)	
	Δ Consumption (kg)	-4.832 (-19.1%)	-0.426 (-1.4%)	-0.269 (-1.2%)	-0.008 (-0.1%)	-5.535 -6.6%)
	Tax revenue (USD)	\$86.42	\$15.02	\$13.42	\$3.54	\$118.40
Climate effect	Δ Emissions (kg CO_2-eq.)	-408.072	-4.205	-3.316	-0.105	-415.697 (-14.9%)
Animal welfare effects	Δ Direct deaths	-0.025	-0.396	-0.006	-0.005	-0.431 (-1.3%)
	Δ Total deaths	-0.028	-0.457	-0.225	-0.046	-0.755 (-0.9%)
	Δ Direct time of suffering (days)	-27.974	-19.392	-0.937	-1.512	-49.814 (-1.9%)
	Δ Total time of suffering (days)	-28.722	-19.741	-1.200	-1.662	-51.324 (-1.8%)

Note: F. fish means farmed fish. Δ means absolute change. Percentage values are in brackets.

Table 13. *Effects of a \$1 tax per animal slaughtered, including fish (per capita per year)*

		Beef	Chicken	Pork	F. fish	Total
Economic effects	Tax (USD/kg)	\$0.01	\$0.93	\$0.02	\$0.60	
	Δ Consumer price (USD/kg)	\$0.03 (0.5%)	\$0.20 (4.3%)	\$0.04 (0.4%)	\$0.31 (1.7%)	
	Δ Producer price (USD/kg)	\$0.03 (0.4%)	-\$0.73 (-16.0%)	\$0.02 (0.2%)	-\$0.29 (-1.6%)	
	Δ Consumption (kg)	0.058 (0.2%)	-1.181 (-3.8%)	0.032 (0.1%)	-0.058 (-1.1%)	-1.150 (-1.4%)
	Tax revenue (USD)	\$0.13	\$27.58	\$0.46	\$3.09	\$31.26
Climate effect	Δ Emissions (kg CO_2-eq.)	4.906	-11.659	0.389	-0.796	-7.160 (-0.3%)
Animal welfare effects	Δ Direct deaths	0.000	-1.097	0.001	-0.035	-1.132 (-3.5%)
	Δ Total deaths	0.000	-1.267	0.026	-0.348	-1.588 (-1.9%)
	Δ Direct time of suffering (days)	0.336	-53.774	0.110	-11.453	-64.781 (-2.4%)
	Δ Total time of suffering (days)	0.345	-54.741	0.141	-12.584	-66.839 (-2.4%)

Note: F. fish means farmed fish. Δ means absolute change. Percentage values are in brackets.

Table 14. *Effects of a $5 tax per animal slaughtered, including fish (per capita per year)*

		Beef	Chicken	Pork	F. fish	Total
Economic effects	Tax (USD/kg)	$0.03	$4.65	$0.10	$3.01	
	Δ Consumer price (USD/kg)	$0.22 (2.9%)	$1.48 (32.3%)	$0.24 (2.7%)	$1.69 (9.2%)	
	Δ Producer price (USD/kg)	$0.19 (2.6%)	-$3.17 (-69.0%)	$0.14 (1.5%)	-$1.32 (-7.1%)	
	Δ Consumption (kg)	0.392 (1.5%)	-7.130 (-23.1%)	0.223 (1.0%)	-0.264 (-5.1%)	-6.780 (-8.1%)
	Tax revenue (USD)	$0.68	$110.27	$2.31	$14.84	$128.10
Climate effect	Δ Emissions (kg CO_2-eq.)	33.089	-70.374	2.741	-3.599	-38.143 (-1.4%)
Animal welfare effects	Δ Direct deaths	0.002	-6.624	0.005	-0.159	-6.776 (-20.9%)
	Δ Total deaths	0.002	-7.646	0.186	-1.572	-9.030 (-10.9%)
	Δ Direct time of suffering (days)	2.268	-324.571	0.774	-51.805	-373.334 (-14.1%)
	Δ Total time of suffering (days)	2.329	-330.408	0.992	-56.919	-384.006 (-13.7%)

Note: F. fish means farmed fish. Δ means absolute change. Percentage values are in brackets.

Table 15. *Effects of a $1 tax per kg meat or fish (per capita per year)*

		Beef	Chicken	Pork	F. fish	Total
Economic effects	Tax (USD/kg)	$1.00	$1.00	$1.00	$1.00	
	Δ Consumer price (USD/kg)	$0.48 (6.5%)	$0.26 (5.6%)	$0.51 (5.6%)	$0.64 (3.5%)	
	Δ Producer price (USD/kg)	-$0.52 (-7.0%)	-$0.74 (-16.2%)	-$0.49 (-5.5%)	-$0.36 (-1.9%)	
	Δ Consumption (kg)	-1.089 (-4.3%)	-1.197 (-3.9%)	-0.806 (-3.7%)	-0.071 (-1.4%)	-3.164 (-3.8%)
	Tax revenue (USD)	$24.21	$29.67	$21.27	$5.13	$80.27
Climate effect	Δ Emissions (kg CO_2-eq.)	-91.979	-11.814	-9.926	-0.970	-114.690 (-4.1%)
Animal welfare effects	Δ Direct deaths	-0.006	-1.112	-0.017	-0.043	-1.177 (-3.6%)
	Δ Total deaths	-0.006	-1.284	-0.672	-0.424	-2.386 (-2.9%)
	Δ Direct time of suffering (days)	-6.305	-54.488	-2.804	-13.969	-77.566 (-2.9%)
	Δ Total time of suffering (days)	-6.474	-55.468	-3.592	-15.348	-80.881 (-2.9%)

Note: F. fish means farmed fish. Δ means absolute change. Percentage values are in brackets.

Table 16. *Effects of a $5 tax per kg meat or fish (per capita per year)*

		Beef	**Chicken**	**Pork**	**F. fish**	**Total**
Economic effects	Tax (USD/kg)	$5.00	$5.00	$5.00	$5.00	
	Δ Consumer price (USD/kg)	$2.79 (37.7%)	$1.85 (40.3%)	$2.84 (31.4%)	$3.46 (18.7%)	
	Δ Producer price (USD/kg)	-$2.21 (-29.9%)	-$3.15 (-68.8%)	-$2.16 (-23.9%)	-$1.54 (-8.4%)	
	Δ Consumption (kg)	-4.901 (-19.4%)	-7.084 (-22.9%)	-3.654 (-16.6%)	-0.310 (-6.0%)	-15.95 (-19.1%)
	Tax revenue (USD)	$101.97	$118.92	$92.09	$24.44	$337.42
Climate effect	Δ Emissions (kg CO_2-eq.)	-413.903	-69.922	-44.986	-4.231	-533.043 (-19.1%)
Animal welfare effects	Δ Direct deaths	-0.026	-6.581	-0.076	-0.187	-6.870 (-21.2%)
	Δ Total deaths	-0.028	-7.597	-3.047	-1.848	-12.520 (-15.2%)
	Δ Direct time of suffering (days)	-28.373	-322.488	-12.708	-60.908	-424.478 (-16.0%)
	Δ Total time of suffering (days)	-29.133	-328.287	-16.277	-66.921	-440.618 (-15.7%)

Note: F. fish means farmed fish. Δ means absolute change. Percentage values are in brackets.

Appendix E – Robustness check results (doubled cross-price elasticities of demand)

Table 17. *Effects of a $25 tax per tonne of CO_2-eq. GHG emissions (per capita per year) with doubled cross-price elasticities of demand*

		Beef	Chicken	Pork	F. fish	Total
Economic effects	Tax (USD/kg)	$2.11	$0.25	$0.31	$0.34	
	Δ Consumer price (USD/kg)	$1.02 (13.8%)	$0.20 (4.3%)	$0.37 (4.1%)	$0.63 (3.4%)	
	Δ Producer price (USD/kg)	-$1.09 (-14.8%)	-$0.05 (-1.1%)	$0.06 (0.7%)	$0.29 (1.6%)	
	Δ Consumption (kg)	-2.340 (-9.3%)	-0.078 (-0.3%)	0.095 (0.4%)	0.057 (1.1%)	-2.266 (-2.7%)
	Tax revenue (USD)	$48.47	$7.60	$6.82	$1.79	$64.68
Climate effect	Δ Emissions (kg CO_2-eq.)	-197.628	-0.773	1.172	0.774	-196.455 (-7.1%)
Animal welfare effects	Δ Direct deaths	-0.012	-0.073	0.002	0.034	-0.049 (-0.2%)
	Δ Total deaths	-0.013	-0.084	0.079	0.338	0.320 (0.4%)
	Δ Direct time of suffering (days)	-13.548	-3.563	0.331	11.137	-5.643 (-0.2%)
	Δ Total time of suffering (days)	-13.910	-3.628	0.424	12.236	-4.878 (-0.2%)
SCAU thresholds	Θ_{SCAU} (direct deaths)					n/a
	Θ_{SCAU} (total deaths)					0.61404
	Θ_{SCAU} (direct time)					n/a
	Θ_{SCAU} (total time)					n/a

Note: F. fish means farmed fish. Δ means absolute change. Percentage values are in brackets.

Table 18. *Effects of a $2.50 tax per animal slaughtered, including fish (per capita per year) with doubled cross-price elasticities of demand*

		Beef	**Chicken**	**Pork**	**F. fish**	**Total**
Economic effects	Tax (USD/kg)	$0.01	$2.32	$0.05	$1.50	
	Δ Consumer price (USD/kg)	$0.21 (2.9%)	$0.61 (13.4%)	$0.24 (2.7%)	$1.09 (5.9%)	
	Δ Producer price (USD/kg)	$0.20 (2.7%)	-$1.71 (-37.3%)	$0.19 (2.1%)	-$0.42 (-2.3%)	
	Δ Consumption (kg)	0.408 (1.6%)	-3.062 (-9.9%)	0.306 (1.4%)	-0.083 (-1.6%)	-2.430 (-2.9%)
	Tax revenue (USD)	$0.34	$64.58	$1.16	$7.69	$73.77
Climate effect	Δ Emissions (kg CO_2-eq.)	34.480	-30.219	3.768	-1.130	6.900 (0.2%)
Animal welfare effects	Δ Direct deaths	0.002	-2.844	0.006	-0.050	-2.886 (-8.9%)
	Δ Total deaths	0.002	-3.283	0.255	-0.494	-3.519 (-4.3%)
	Δ Direct time of suffering (days)	2.364	-139.370	1.064	-16.265	-152.207 (-5.7%)
	Δ Total time of suffering (days)	2.427	-141.877	1.363	-17.870	-155.957 (-5.6%)
SCAU thresholds	Θ_{SCAU} (direct deaths)					0.00239
	Θ_{SCAU} (total deaths)					0.00196
	Θ_{SCAU} (direct time)					0.00005
	Θ_{SCAU} (total time)					0.00004

Note: F. fish means farmed fish. Δ means absolute change. Percentage values are in brackets.

Table 19. *Effects of a $2.50 tax per kg meat or fish (per capita per year) with doubled cross-price elasticities of demand*

		Beef	Chicken	Pork	F. fish	Total
Economic effects	Tax (USD/kg)	$2.50	$2.50	$2.50	$2.50	
	Δ Consumer price (USD/kg)	$1.56 (21.1%)	$0.94 (20.6%)	$1.68 (18.7%)	$2.59 (14.0%)	
	Δ Producer price (USD/kg)	-$0.94 (-12.7%)	-$1.56 (-34.0%)	-$0.82 (-9.0%)	$0.09 (0.5%)	
	Δ Consumption (kg)	-1.997 (-7.9%)	-2.740 (-8.9%)	-1.341 (-6.1%)	0.018 (0.3%)	-6.060 (-7.3%)
	Tax revenue (USD)	$58.25	$70.32	$51.83	$13.04	$193.43
Climate effect	Δ Emissions (kg CO_2-eq.)	-168.681	-27.040	-16.511	0.242	-211.990 (-7.6%)
Animal welfare effects	Δ Direct deaths	-0.011	-2.545	-0.028	0.011	-2.573 (-7.9%)
	Δ Total deaths	-0.011	-2.938	-1.118	0.106	-3.962 (-4.8%)
	Δ Direct time of suffering (days)	-11.563	-124.710	-4.664	3.482	-137.456 (-5.2%)
	Δ Total time of suffering (days)	-11.873	-126.953	-5.974	3.826	-140.974 (-5.0%)
SCAU thresholds	Θ_{SCAU} (direct deaths)					n/a
	Θ_{SCAU} (total deaths)					n/a
	Θ_{SCAU} (direct time)					n/a
	Θ_{SCAU} (total time)					n/a

Note: F. fish means farmed fish. Δ means absolute change. Percentage values are in brackets.

Appendix F – Robustness check results (less own-price elastic demand)

This appendix presents the results for the calibration that uses the own-price elasticity of demand estimates by Andreyeva et al. (2010) rather than Bouyssou et al. (2024).

Table 20. *Effects of a \$25 tax per tonne of CO_2-eq. GHG emissions (per capita per year) with less elastic demand*

		Beef	Chicken	Pork	F. fish	Total
Economic effects	Tax (USD/kg)	\$2.11	\$0.25	\$0.31	\$0.34	
	Δ Consumer price (USD/kg)	\$1.07 (14.4%)	\$0.16 (3.4%)	\$0.28 (3.2%)	\$0.52 (2.8%)	
	Δ Producer price (USD/kg)	-\$1.05 (-14.1%)	-\$0.09 (-2.0%)	-\$0.02 (-0.3%)	\$0.18 (1.0%)	
	Δ Consumption (kg)	-2.233 (-8.8%)	-0.136 (-0.4%)	-0.038 (-0.2%)	0.036 (0.7%)	-2.371 (-2.8%)
	Tax revenue (USD)	\$48.70	\$7.58	\$6.78	\$1.78	\$64.84
Climate effect	Δ Emissions (kg CO_2-eq.)	-188.600	-1.346	-0.463	0.488	-189.922 (-6.8%)
Animal welfare effects	Δ Direct deaths	-0.012	-0.127	-0.001	0.022	-0.118 (-0.4%)
	Δ Total deaths	-0.013	-0.146	-0.031	0.213	0.022 (0.0%)
	Δ Direct time of suffering (days)	-12.929	-6.210	-0.131	7.019	-12.251 (-0.5%)
	Δ Total time of suffering (days)	-13.275	-6.322	-0.168	7.712	-12.052 (-0.4%)
SCAU thresholds	Θ_{SCAU} (direct deaths)					n/a
	Θ_{SCAU} (total deaths)					8.452
	Θ_{SCAU} (direct time)					n/a
	Θ_{SCAU} (total time)					n/a

Note: F. fish means farmed fish. Δ means absolute change. Percentage values are in brackets.

Table 21. *Effects of a $2.50 tax per animal slaughtered, including fish (per capita per year) with less elastic demand*

		Beef	Chicken	Pork	F. fish	Total
Economic effects	Tax (USD/kg)	$0.01	$2.32	$0.05	$1.50	
	Δ Consumer price (USD/kg)	$0.14 (1.8%)	$0.75 (16.3%)	$0.17 (1.8%)	$1.24 (6.7%)	
	Δ Producer price (USD/kg)	$0.12 (1.7%)	-$1.58 (-34.4%)	$0.11 (1.3%)	-$0.26 (-1.4%)	
	Δ Consumption (kg)	0.252 (1.0%)	-2.781 (-9.0%)	0.183 (0.8%)	-0.052 (-1.0%)	-2.397 (-2.9%)
	Tax revenue (USD)	$0.34	$65.23	$1.15	$7.74	$74.46
Climate effect	Δ Emissions (kg CO_2-eq.)	21.325	-27.450	2.258	-0.709	-4.576 (-0.2%)
Animal welfare effects	Δ Direct deaths	0.001	-2.584	0.004	-0.031	-2.610 (-8.1%)
	Δ Total deaths	0.001	-2.982	0.153	-0.310	-3.138 (-3.8%)
	Δ Direct time of suffering (days)	1.462	-126.603	0.638	-10.207	-134.710 (-5.1%)
	Δ Total time of suffering (days)	1.501	-128.879	0.817	-11.214	-137.775 (-4.9%)
SCAU thresholds	Θ_{SCAU} (direct deaths)					n/a
	Θ_{SCAU} (total deaths)					n/a
	Θ_{SCAU} (direct time)					n/a
	Θ_{SCAU} (total time)					n/a

Note: F. fish means farmed fish. Δ means absolute change. Percentage values are in brackets.

Table 22. *Effects of a $2.50 tax per kg meat or fish (per capita per year) with less elastic demand*

		Beef	Chicken	Pork	F. fish	Total
Economic effects	Tax (USD/kg)	$2.50	$2.50	$2.50	$2.50	
	Δ Consumer price (USD/kg)	$1.48 (20.1%)	$0.99 (21.6%)	$1.62 (17.9%)	$2.60 (14.1%)	
	Δ Producer price (USD/kg)	-$1.02 (-13.8%)	-$1.51 (-32.9%)	-$0.88 (-9.8%)	$0.10 (0.5%)	
	Δ Consumption (kg)	-2.169 (-8.6%)	-2.640 (-8.6%)	-1.453 (-6.6%)	0.020 (0.4%)	-6.242 (-7.5%)
	Tax revenue (USD)	$57.81	$70.57	$51.55	$13.04	$192.98
Climate effect	Δ Emissions (kg CO_2-eq.)	-183.215	-26.054	-17.887	0.270	-226.887 (-8.2%)
Animal welfare effects	Δ Direct deaths	-0.011	-2.452	-0.030	0.012	-2.482 (-7.7%)
	Δ Total deaths	-0.012	-2.831	-1.211	0.118	-3.936 (-4.8%)
	Δ Direct time of suffering (days)	-12.559	-120.165	-5.053	3.893	-133.885 (-5.1%)
	Δ Total time of suffering (days)	-12.896	-122.326	-6.472	4.278	-137.417 (-4.9%)
SCAU thresholds	Θ_{SCAU} (direct deaths)					n/a
	Θ_{SCAU} (total deaths)					n/a
	Θ_{SCAU} (direct time)					n/a
	Θ_{SCAU} (total time)					n/a

Note: F. fish means farmed fish. Δ means absolute change. Percentage values are in brackets.

Appendix G – Robustness check results (perfect elasticity of supply)

Table 23. *Effects of a \$25 tax per tonne of CO_2-eq. GHG emissions (per capita per year) under perfect elasticity of supply*

		Beef	Chicken	Pork	F. fish	Total
Economic effects	Tax (USD/kg)	\$2.11	\$0.25	\$0.31	\$0.34	
	Δ Consumer price (USD/kg)	\$2.11 (28.6%)	\$0.25 (5.4%)	\$0.31 (3.4%)	\$0.34 (1.8%)	
	Δ Producer price (USD/kg)	\$0.00 (0.0%)	\$0.00 (0.0%)	\$0.00 (0.0%)	\$0.00 (0.0%)	
	Δ Consumption (kg)	-4.998 (-19.8%)	-0.661 (-2.1%)	0.038 (0.2%)	0.071 (1.4%)	-5.550 (-6.7%)
	Tax revenue (USD)	\$42.86	\$7.45	\$6.80	\$1.80	\$58.91
Climate effect	Δ Emissions (kg CO_2-eq.)	-422.125	-6.526	0.464	0.968	-427.219 (-15.3%)
Animal welfare effects	Δ Direct deaths	-0.026	-0.614	0.001	0.043	-0.597 (-1.8%)
	Δ Total deaths	-0.029	-0.709	0.031	0.423	-0.284 (-0.3%)
	Δ Direct time of suffering (days)	-28.937	-30.098	0.131	13.931	-44.973 (-1.7%)
	Δ Total time of suffering (days)	-29.711	-30.639	0.168	15.306	-44.877 (-1.6%)
SCAU thresholds	Θ_{SCAU} (direct deaths)					n/a
	Θ_{SCAU} (total deaths)					n/a
	Θ_{SCAU} (direct time)					n/a
	Θ_{SCAU} (total time)					n/a

Note: F. fish means farmed fish. Δ means absolute change. Percentage values are in brackets.

Table 24. *Effects of a $2.50 tax per animal slaughtered, including fish (per capita per year) under perfect elasticity of supply*

		Beef	Chicken	Pork	F. fish	Total
Economic effects	Tax (USD/kg)	$0.01	$2.32	$0.05	$1.50	
	Δ Consumer price (USD/kg)	$0.01 (0.2%)	$2.32 (50.7%)	$0.05 (0.6%)	$1.50 (8.1%)	
	Δ Producer price (USD/kg)	$0.00 (0.0%)	$0.00 (0.0%)	$0.00 (0.0%)	$0.00 (0.0%)	
	Δ Consumption (kg)	1.420 (5.6%)	-10.085 (-32.7%)	0.815 (3.7%)	-0.171 (-3.3%)	-8.021 (-9.6%)
	Tax revenue (USD)	$0.35	$48.27	$1.18	$7.56	$57.37
Climate effect	Δ Emissions (kg CO_2-eq.)	119.930	-99.540	10.033	-2.325	28.098 (1.0%)
Animal welfare effects	Δ Direct deaths	0.007	-9.369	0.017	-0.103	-9.447 (-29.2%)
	Δ Total deaths	0.008	-10.814	0.680	-1.016	-11.142 (-13.5%)
	Δ Direct time of suffering (days)	8.221	-459.086	2.834	-33.471	-481.501 (-18.2%)
	Δ Total time of suffering (days)	8.441	-467.341	3.630	-36.775	-492.044 (-0.176
SCAU thresholds	Θ_{SCAU} (direct deaths)					0.00297
	Θ_{SCAU} (total deaths)					0.00252
	Θ_{SCAU} (direct time)					0.00006
	Θ_{SCAU} (total time)					0.00006

Note: F. fish means farmed fish. Δ means absolute change. Percentage values are in brackets.

Table 25. *Effects of a $2.50 tax per kg meat or fish (per capita per year) under perfect elasticity of supply*

		Beef	Chicken	Pork	F. fish	Total
Economic effects	Tax (USD/kg)	\$2.50	\$2.50	\$2.50	\$2.50	
	Δ Consumer price (USD/kg)	\$2.50 (33.8%)	\$2.50 (54.5%)	\$2.50 (27.7%)	\$2.50 (13.5%)	
	Δ Producer price (USD/kg)	\$0.00 (0.0%)	\$0.00 (0.0%)	\$0.00 (0.0%)	\$0.00 (0.0%)	
	Δ Consumption (kg)	-4.183 (-16.5%)	-9.425 (-30.5%)	-3.142 (-14.2%)	-0.060 (-1.1%)	-16.810 (-20.1%)
	Tax revenue (USD)	\$52.78	\$53.61	\$47.32	\$12.85	\$166.56
Climate effect	Δ Emissions (kg CO_2-eq.)	-353.310	-93.024	-38.676	-0.813	-485.823 (-17.5%)
Animal welfare effects	Δ Direct deaths	-0.022	-8.756	-0.065	-0.036	-8.879 (-27.4%)
	Δ Total deaths	-0.024	-10.107	-2.619	-0.355	-13.105 (-15.9%)
	Δ Direct time of suffering (days)	-24.220	-429.035	-10.925	-11.700	-475.880 (-18.0%)
	Δ Total time of suffering (days)	-24.868	-436.749	-13.994	-12.856	-488.467 (-17.4%)
SCAU thresholds	Θ_{SCAU} (direct deaths)					n/a
	Θ_{SCAU} (total deaths)					n/a
	Θ_{SCAU} (direct time)					n/a
	Θ_{SCAU} (total time)					n/a

Note: F. fish means farmed fish. Δ means absolute change. Percentage values are in brackets.

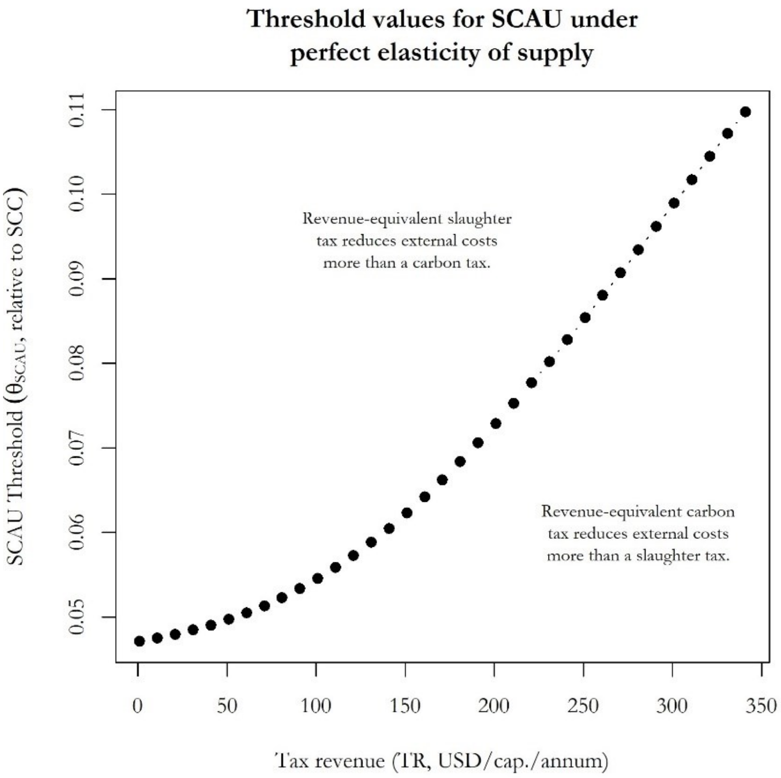

Figure 3. *Threshold values for SCAU under perfect elasticity of supply*

Appendix H – Robustness check results (no taxes on fish)

Table 26. *Effects of a \$25 tax per tonne of CO_2- eq. GHG emissions (per capita per year) with a tax exemption for fish*

		Beef	Chicken	Pork	F. fish	Total
Economic effects	Tax (USD/kg)	\$2.11	\$0.25	\$0.31	\$0.00	
	Δ Consumer price (USD/kg)	\$0.94 (12.7%)	\$0.10 (2.3%)	\$0.22 (2.4%)	\$0.18 (1.0%)	
	Δ Producer price (USD/kg)	-\$1.17 (-15.8%)	-\$0.14 (-3.1%)	-\$0.09 (-1.0%)	\$0.18 (1.0%)	
	Δ Consumption (kg)	-2.509 (-9.9%)	-0.217 (-0.7%)	-0.148 (-0.7%)	0.035 (0.7%)	-2.838 (-3.4%)
	Tax revenue (USD)	\$48.11	\$7.56	\$6.75	\$0.00	\$62.42
Climate effect	Δ Emissions (kg CO_2-eq.)	-211.894	-2.144	-1.816	0.482	-215.373 (-7.7%)
Animal welfare effects	Δ Direct deaths	-0.013	-0.202	-0.003	0.021	-0.197 (-0.6%)
	Δ Total deaths	-0.014	-0.233	-0.123	0.210	-0.160 (-0.2%)
	Δ Direct time of suffering (days)	-14.525	-9.890	-0.513	6.933	-17.995 (-0.7%)
	Δ Total time of suffering (days)	-14.914	-10.068	-0.657	7.618	-18.022 (-0.6%)
SCAU thresholds	Θ_{SCAU} (direct deaths)					n/a
	Θ_{SCAU} (total deaths)					n/a
	Θ_{SCAU} (direct time)					n/a
	Θ_{SCAU} (total time)					n/a

Note: F. fish means farmed fish. ⊿ means absolute change. Percentage values are in brackets.

Table 27. *Effects of a $2.50 tax per animal slaughtered, excluding fish (per capita per year)*

		Beef	**Chicken**	**Pork**	**F. fish**	**Total**
Economic effects	Tax (USD/kg)	$0.01	$2.32	$0.05	$0.00	
	Δ Consumer price (USD/kg)	$0.08 (1.1%)	$0.55 (12.1%)	$0.08 (0.9%)	$0.17 (0.9%)	
	Δ Producer price (USD/kg)	$0.07 (1.0%)	-$1.77 (-38.6%)	$0.03 (0.4%)	$0.17 (0.9%)	
	Δ Consumption (kg)	0.146 (0.6%)	-3.192 (-10.3%)	0.053 (0.2%)	0.033 (0.6%)	-2.959 (-3.5%)
	Tax revenue (USD)	$0.34	$64.28	$1.14	$0.00	$65.76
Climate effect	Δ Emissions (kg CO_2-eq.)	12.347	-31.505	0.657	0.456	-18.044 (-0.6%)
Animal welfare effects	Δ Direct deaths	0.001	-2.965	0.001	0.020	-2.943 (-9.1%)
	Δ Total deaths	0.001	-3.423	0.045	0.199	-3.178 (-3.8%)
	Δ Direct time of suffering (days)	0.846	-145.302	0.186	6.570	-137.700 (-5.2%)
	Δ Total time of suffering (days)	0.869	-147.915	0.238	7.218	-139.590 (-5.0%)
SCAU thresholds	Θ_{SCAU} (direct deaths)					n/a
	Θ_{SCAU} (total deaths)					n/a
	Θ_{SCAU} (direct time)					n/a
	Θ_{SCAU} (total time)					n/a

Note: F. fish means farmed fish. ⊿ means absolute change. Percentage values are in brackets.

Table 28. *Effects of a $2.50 tax per kg meat (per capita per year) with a tax exemption for fish*

		Beef	Chicken	Pork	F. fish	Total
Economic effects	Δ Tax (USD/kg)	$2.50	$2.50	$2.50	$0.00	
	Δ Consumer price (USD/kg)	$1.26 (17.1%)	$0.71 (15.6%)	$1.29 (14.3%)	$0.59 (3.2%)	
	Δ Producer price (USD/kg)	-$1.24 (-16.7%)	-$1.79 (-39.0%)	-$1.21 (-13.4%)	$0.59 (3.2%)	
	Δ Consumption (kg)	-2.654 (-10.5%)	-3.231 (-10.5%)	-2.010 (-9.1%)	0.117 (2.3%)	-7.777 (-9.3%)
	Tax revenue (USD)	$56.60	$69.09	$50.16	$0.00	$175.85
Climate effect	Δ Emissions (kg CO_2-eq.)	-224.175	-31.891	-24.738	1.600	-279.203 (-10.0%)
Animal welfare effects	Δ Direct deaths	-0.014	-3.002	-0.042	0.071	-2.987 (-9.2%)
	Δ Total deaths	-0.015	-3.465	-1.675	0.699	-4.456 (-5.4%)
	Δ Direct time of suffering (days)	-15.367	-147.082	-6.988	23.033	-146.405 (-5.5%)
	Δ Total time of suffering (days)	-15.779	-149.727	-8.951	25.307	-149.150 (-5.3%)
SCAU thresholds	Θ_{SCAU} (direct deaths)					n/a
	Θ_{SCAU} (total deaths)					n/a
	Θ_{SCAU} (direct time)					n/a
	Θ_{SCAU} (total time)					n/a

Note: F. fish means farmed fish. Δ means absolute change. Percentage values are in brackets.