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What are the potential preventive population-health effects of a tax on processed meat? A quantitative health impact assessment for Germany

Johanna-Katharina Schönbach[a,b,*], Silke Thiele[c], Stefan K. Lhachimi[a,b]

[a] Institute for Public Health and Nursing Research, Health Sciences Bremen, University of Bremen, Bibliothekstraße 1, 28359 Bremen, Germany
[b] Research Group for Evidence-Based Public Health, Leibniz Institute for Prevention Research and Epidemiology - BIPS, Achterstraße 30, 28359 Bremen, Germany
[c] ife Institute of Food Economics, Science Park Kiel, Fraunhoferstraße 13, 24118 Kiel, Germany

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ABSTRACT

The International Agency for Research on Cancer considers processed meat to be carcinogenic. Further, processed meat is associated with diabetes, ischemic heart disease (IHD) and all-cause mortality. We aimed to assess health gains of four processed meat taxation scenarios in comparison to the reference and a minimum-risk-exposure-scenario.

To estimate the shift in processed meat intake following respective taxes, we calculated price elasticities for processed meat. DYNAMO-HIA was used to dynamically project policy-attributable differences in the prevalence of diseases and deaths.

In projection year 10, an extra 9300 males and 4500 females would be alive under the lowest tax scenario (4% tax), compared to the reference scenario. Prevalent IHD, diabetes and colorectal cancer cases in males would be 8400, 9500 and 500 lower, respectively, and there would be 4600, 7800 and 300 less cases in females. Of the respective death and disease reduction that would be achieved under the minimum-risk-exposure-scenario, the lowest tax reaches 2.84% (colorectal cancer in males) to 6.02% (diabetes in females). Under the highest tax scenario (33.3% tax), an extra 76,700 males and 37,100 females would be alive, compared to the reference scenario. Prevalent IHD, diabetes and colorectal cancer cases would be 70,800, 77,900 and 4900 lower in males and 29,900, 48,900 and 2300 lower in females, which represents 27.84% (colorectal cancer in males) to 37.76% (diabetes in females) of the maximal preventable death and disease burden.

Further research needs to examine to what extent these health benefits are outweighed by a simultaneous tax-induced decrease in fish intake.

1. Introduction

The health impact of red and processed meat intake gained attention after the International Agency for Research on Cancer (IARC) recently classified processed meat as group 1, i.e. carcinogenic to humans (Bouvard et al., 2015; IARC Working Group on the Evaluation of Carcinogenic Risks to Humans, 2018). Aside from an association between processed meat intake and colorectal cancer (Chan et al., 2011; World Cancer Research Fund, American Institute for Cancer Research, Imperial College London, 2010), there is also evidence for an association between processed meat intake and coronary heart disease (CHD), diabetes and (all-cause) mortality (Abete et al., 2014; Larsson and Orsini, 2014; Micha et al., 2012; Micha et al., 2010; Pan et al., 2011; Rohrmann et al., 2013; Wang et al., 2016).

Suspected underlying mechanism are the formation of heterocyclic amines (HCAs) and polycyclic aromatic hydrocarbons (PAHs) during high temperature cooking, which have carcinogenic effects (Demeyer et al., 2016; IARC Working Group on the Evaluation of Carcinogenic Risks to Humans, 2018; Rohrmann and Linseisen, 2016) and might also increase CHD and diabetes (Micha et al., 2012). Processing procedures to enhance flavour or improve preservation may result in further increased health risks. Salting or curing, i.e. adding salt with or without nitrate, increases the previously relatively low sodium content of unprocessed red meat, which increases blood pressure and effects CHD (Micha et al., 2012). Further, carcinogenic *N*-nitroso compounds (NOCs) can be formed from nitrates (Demeyer et al., 2016; IARC Working Group on the Evaluation of Carcinogenic Risks to Humans, 2018; Rohrmann and Linseisen, 2016).

The Global Burden of Disease (GBD) 2016 Study attributed a burden of 139,600 deaths globally to processed meat intake (GBD 2016 Risk

* Corresponding author at: Institute for Public Health and Nursing Research, Health Sciences Bremen, University of Bremen, Bibliothekstraße 1, 28359 Bremen, Germany.
E-mail address: schoenbach@leibniz-bips.de (J.-K. Schönbach).

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Table 1
Marshallian unconditional own and cross price elasticities with 95% Confidence Intervals, based on 'Gesellschaft für Konsumforschung' (GfK) consumer panel dataset, 2011.

Quantity	Price			
	Red meat	White meat	Fish	Processed meat
Red meat	−0.694 (−0.722 to −0.665)[a]	−0.128 (−0.146 to −0.110)	−0.020 (−0.035 to −0.005)	0.031 (−0.017–0.045)
White meat	−0.179 (−0.218 to −0.141)	−0.487 (−0.524 to −0.450)[a]	−0.031 (−0.054 to −0.008)	0.027 (0.006 to 0.048)
Fish	0.059 (0.014 to 0.103)	−0.023 (−0.045 to 0.008)	−0.477 (−0.517 to −0.438)[a]	−0.161 (−0.185 to −0.137)
Processed meat	0.251 (0.189 to 0.314)	0.083 (0.037 to 0.128)	−0.255 (−0.293 to −0.217)	−0.699 (−0.756 to −0.642)[a]

[a] Own-price elasticities.

Factor Collaborators, 2017). Other studies have evaluated the potentially preventable disease and death burden under eliminated or reduced processed meat intake levels in Europe (Rohrmann et al., 2013), Australia (Nagle et al., 2015), Columbia (de Vries et al., 2017) and the UK (Aston et al., 2012).

The World Health Organization (WHO) suggested the use of fiscal policy in the form of taxation and subsidies, which alter food prices, to provide economic incentives to consumers to improve their diet (World Health Organization, 2015, 2016). A range of studies have already examined the health effects of SSB taxations, fat and junk food taxation, as well as fruit and vegetable subsidization (Basu et al., 2014; Briggs et al., 2013b; Cobiac et al., 2017; Jones et al., 2017; Manyema et al., 2014; Ni Mhurchu et al., 2015; Pearson-Stuttard et al., 2017; Sacks et al., 2011; Schwendicke and Stolpe, 2017; Smith et al., 2010; Veerman et al., 2016). For the U.S., it was estimated that a 10% price increase for processed meat would prevent 2175, or 0.3%, CVD and diabetes deaths annually. A 30% price increase would prevent 6447, or 0.9%, CVD and diabetes deaths per year (Penalvo et al., 2017).

The objective of this study is to dynamically model to what extent respective taxes on processed meat can potentially improve population health (with regard to prevalent cases of IHD, diabetes, colorectal cancer and deaths) for the European context, using the example of Germany.

2. Methods

In our analysis, we estimated the potential health benefits from reduced processed meat intake. To this end, we modeled six scenarios with different levels of processed meat intake 10 years into the future. Our analysis consisted of two steps: first, we calculated the change in processed meat purchases following the respective taxes, based on price elasticities. Second, we modeled the impact of this intake change on health outcomes using DYNAMO-HIA, a dynamic health impact assessment tool (Boshuizen et al., 2012; Lhachimi et al., 2010; Lhachimi et al., 2012b). An overview of all data sources is given in Supplemental Table 1.

2.1. Policy proposal and scenarios

We modeled the following scenarios, which are fully described in Supplemental Table 2.

- Reference scenario: keeps current processed meat intake constant;
- Scenario 1: a "minimum environmental tax" on processed meat with a price increase of 4%;
- Scenario 2: a "modification of the value-added tax (VAT)", which removes the financially advantageous VAT reduction on processed meat, translating to a price increase of 11.2%;
- Scenario 3: a "modest environmental tax" on processed meat with a price increase of 18.5%;
- Scenario 4: a "maximum environmental tax" on processed meat with a price increase of 33.3%;
- Minimum-risk-exposure-scenario: assumes a per capita processed meat intake of < 15 g/day. This scenario was used for comparison purposes to estimate the maximal reducible burden induced by processed meat intake.

2.2. Price elasticities

To determine the effect of taxes on demand, we estimated own-and cross-price elasticities for German households. The price elasticities express the percentage change in quantitative processed meat demand (own-price elasticity) or in other food groups such as fish, unprocessed red meat and white meat (cross-price elasticity) in response to a 1% change in the price of processed meat (Nghiem et al., 2013). We calculated these price elasticities using the well-established Almost Ideal Demand System (AIDS), and a consumer panel dataset collected from January to December 2011 by the German 'Gesellschaft für Konsumforschung' (GfK) (see Supplemental Text 1 for detailed calculations, Supplemental Table 3 for descriptive statistics of the purchases of meat and fish in the GfK consumer panel dataset, and Supplemental Table 4 for estimation results of the AIDS). The GfK-data cover all food purchases of 13,125 representative German households, which were asked to document their purchases for at least ten months per year using a bar code scanner. A resulting 12,408,473 food purchases, including price, quantity and several further information, were collected by the GfK (Thiele et al., 2017). In preparation for the calculation of price elasticities the individual purchases were classified into main food groups such as fruits, vegetables, meat/fish products etc. For this analysis the meat and fish group was further subdivided into the four subgroups "red meat", "white meat", "fish" and "processed meat".

The unconditional price elasticities are presented in Table 1. Even though there is uncertainty around how the industry would react, there is evidence from other countries that food taxes were fully passed onto consumers (Colchero et al., 2016). In the simulation we therefore assumed that the taxes have a 100% pass on rate to consumers. Accordingly, a 10% price increase for processed meat results in a 6.99% (95% CI 7.56% to 6.42%) consumption decrease. A 4%, 11.2%, 18.5% and 33.3% price increase of processed meat results in a 2.8%, 7.8%, 12.9% and 23.3% intake drop, respectively. At the same time, our cross-price elasticities indicate that a 10% price increase of processed meat simultaneously results in a 0.31% increase of red meat, a 0.27% increase of white meat, as well as a 1.61% decrease of fish intake.

2.3. Processed meat intake over scenarios

We obtained data on processed meat intake from the German National Nutrition Survey II (NVSII) public use file (Max Rubner-Institut (MRI), 2009). The NVSII is a nationwide representative food consumption survey that was conducted between November 2005 and January 2007. In the survey, 15,371 persons completed the diet history interviews and reported the foods and beverages they had consumed over the preceding 4 weeks (Heuer et al., 2015). We used the NVSII's category "sausages/meat products" as the amount of individual baseline processed meat consumption in grams per day. Tax-induced intake changes were applied to this individual, continuous data. However, for

the analysis we categorized processed meat intake (0– < 15 g/day, 15– < 30 g/day, 30– < 45 g/day, 45– < 60 g/day, 60– < 75 g/day, 75– < 90 g/day, 90– < 105 g/day, 105– < 120 g/day, 120– < 135 g/day, ≥135 g/day) and obtained the proportion of persons in each category, for each age and sex. In order to avoid the occurrence of unsteadiness between consecutive ages due to small sample sizes, these intake prevalences were smoothed over age using multinomial P-splines (Lhachimi et al., 2013; van de Kassteele et al., 2012). The shift of processed meat intake across the different scenarios, for males and females, respectively, is tabulated by age and sex in Supplemental Tables 5–10.

2.4. Epidemiological data on the German population, CHD, diabetes and cancer

Data on the German population (size, age-composition, projected births, mortality) as well as data on disease incidence, prevalence and excess mortality were obtained from the DYNAMO-HIA database (Lhachimi et al., 2012b). The data itself and reports detailing the process of how data was compiled is available from the project's website (https://www.dynamo-hia.eu).

2.5. Relative risks

Relative risks relating each 50 g increment consumption of processed meat with all-cause mortality and disease incidence were taken from the literature (GBD 2016 Risk Factor Collaborators, 2017; Rohrmann et al., 2013). We transformed these relative risks as described in Supplemental Text 2, in order to obtain relative risks matching our intake categories from 0– < 15 g/day to ≥135 g/day (see Table 2).

2.6. Dynamic modeling

DYNAMO-HIA is a software tool which dynamically projects a real-life population through risk factor exposure and a range of associated diseases. In the simulation, it compares the effects of intervention scenarios with a changed risk factor exposure to a reference scenario with unchanged risk factor exposure. At its core, DYNAMO-HIA is based on a Markov-Model, consisting of a micro and a macro simulation. In the micro-simulation of risk factors, age and sex-specific transition probabilities between risk-factor states are used to simulate the annual risk factor distribution in a sample of persons. In the macro-simulation of diseases, disease life tables are constructed for each of the risk-factor biographies. Full technical details are available elsewhere (Boshuizen et al., 2012; Lhachimi et al., 2010; Lhachimi et al., 2012b).

2.7. Sensitivity analysis

We carried out a probabilistic sensitivity analysis (PSA) along the lines of Hendriksen et al. (2015) to estimate the effect of uncertainty around the key model input variables processed meat intake, own-price elasticity of processed meat as well as relative risk of processed meat intake on mortality. This is a partial PSA in the sense that we did not explicitly model the uncertainty in the prevalence or incidence of the included diseases, as the focus of our calculation lies on quantifying the difference between different scenarios (Meier et al., 2016). We ran 1000 repeated replications of the model, for which we obtained a new parameter set of these key model input variables by drawing randomly from specified distributions. For the own-price elasticity of processed meat (−0.699, 95% CI −0.756 to −0.642, see Table 1), we assumed a normal distribution. In order to obtain new age- and sex-specific proportions of persons over the ten intake categories, we drew randomly from a Dirichlet distribution. For the relative risk of processed meat intake on mortality (1.18, 95% CI 1.11 to 1.25, see Table 2), we assumed a lognormal distribution (Briggs et al., 2006; Gray et al., 2010). Confidence intervals for the 1000 simulations are reported in Tables 3 and 4.

3. Results

3.1. Prevalence of disease cases in projection year 10

Table 3 shows the number of prevalent IHD, diabetes and colorectal cancer cases under each of the scenarios in projection year 10 as well as the corresponding number of prevented cases relative to the reference scenario. In all scenarios, the number of prevalent disease cases is reduced, compared to the reference scenario.

Under the minimum-risk-exposure-scenario, which represents the maximal preventable disease burden, there would be 245,900, 268,400 and 17,600 less prevalent IHD, diabetes and colorectal cancer cases in males, respectively, as well as 81,100, 129,500 and 6500 less prevalent IHD, diabetes and colorectal cancer cases in females, compared to the reference scenario.

The lowest tax of 4% would reduce the number of prevalent IHD cases by 8400 in males and 4600 in females relative to the reference scenario; there would be 9500 less prevalent diabetes cases in males and 7800 in females; and the number of prevalent colorectal cancer cases would be reduced by 500 and 300 in males and females, respectively. Thus, the lowest tax of 4% reaches 2.84–6.02% of the maximal preventable disease burden.

Under the highest tax of 33.3%, the number of prevalent IHD cases would be reduced by 70,800 in males and 29,900 in females relative to the reference scenario; there would be 77,900 less prevalent diabetes cases in males and 48,900 in females; and the number of prevalent colorectal cancer cases would be reduced by 4900 and 2300 in males and females, respectively. Thus, the highest tax of 33.3% in scenario 4 reaches 27.84%–37.76% of the maximal preventable disease burden.

3.2. Deaths postponed and lives saved in projection year 10

Table 4 shows the population size under each scenario in projection year 10 as well as the corresponding number of prevented deaths relative to the reference scenario. Under all scenarios, deaths are postponed for males and for females relative to the reference scenario.

Under the minimum-risk-exposure-scenario, which represents the maximal number of preventable deaths, 268,700 more males and 108,200 more females would be alive compared to the reference scenario. In the tax scenarios, prevented deaths range from 9300 males and 4500 females under the lowest tax of 4% to 76,700 males and 37,100 females under the highest tax of 33.3% relative to the reference scenario. Thus, the lowest tax of 4% reaches 3.46% the maximal number of preventable deaths in males and 4.16% in females. The highest tax of 33.3% reaches 28.54% and 34.29% of the maximal number of preventable deaths in males and females, respectively.

4. Discussion

4.1. Main findings

We simulated several policy scenarios that were assumed to increase the prices for processed meat, in order to examine the extent to which respective taxes on processed meat can potentially improve population health outcomes over a projection period of 10 years. The lowest tax scenario (4% tax) reaches 3.46% of the maximal number of preventable deaths in males and 4.16% in females. Of the maximal number of preventable disease cases, it reaches 2.84% (colorectal cancer in males) to 6.02% (diabetes in females). The highest tax of 33.3% is estimated to reach approximately 28.54% of the maximal number of preventable deaths in males and 34.29% and females. It reaches 27.84% (colorectal cancer in males) to 37.76% (diabetes in females) of the maximal preventable disease cases. The difference between males and females can

Table 2
Relative risks of processed meat on all-cause mortality and disease incidence[a].

Age	Processed meat intake categories (g/day)									
	0 < 15	15 < 30	30 < 45	45 < 60	60 < 75	75 < 90	90 < 105	105 < 120	120 < 135	≥135
Relative risks of processed meat intake on all-cause-mortality[b]										
0–24	1	1	1	1	1	1	1	1	1	1
25–95	1	1.03	1.08	1.13	1.19	1.25	1.31	1.38	1.45	1.53
Relative risks of processed meat intake on IHD[c]										
0–24	1	1	1	1	1	1	1	1	1	1
25–29	1	1.15	1.53	2.03	2.69	3.57	4.74	6.29	8.35	11.08
30–34	1	1.12	1.4	1.76	2.21	2.76	3.47	4.34	5.45	6.83
35–39	1	1.08	1.28	1.5	1.77	2.08	2.45	2.88	3.39	3.99
40–44	1	1.07	1.22	1.39	1.58	1.8	2.05	2.34	2.66	3.03
45–49	1	1.07	1.22	1.39	1.58	1.8	2.05	2.34	2.67	3.04
50–54	1	1.06	1.21	1.37	1.55	1.76	2	2.26	2.57	2.91
55–59	1	1.06	1.19	1.33	1.5	1.68	1.88	2.11	2.37	2.66
60–64	1	1.05	1.17	1.3	1.45	1.61	1.79	1.99	2.21	2.45
65–69	1	1.05	1.16	1.28	1.41	1.55	1.71	1.89	2.08	2.3
70–74	1	1.05	1.15	1.26	1.37	1.51	1.65	1.81	1.98	2.17
75–79	1	1.04	1.14	1.23	1.34	1.46	1.59	1.73	1.88	2.05
80–84	1	1.03	1.11	1.18	1.27	1.35	1.45	1.55	1.66	1.77
85–89	1	1.03	1.11	1.18	1.27	1.35	1.45	1.55	1.66	1.77
90–94	1	1.03	1.11	1.18	1.27	1.35	1.45	1.55	1.66	1.77
95	1	1.03	1.11	1.18	1.27	1.35	1.45	1.55	1.66	1.77
Relative risks of processed meat intake on Diabetes[d]										
0–24	1	1	1	1	1	1	1	1	1	1
25–29	1	1.1	1.35	1.64	2.01	2.45	2.98	3.64	4.44	5.42
30–34	1	1.1	1.34	1.63	1.98	2.4	2.92	3.54	4.3	5.23
35–39	1	1.1	1.33	1.61	1.94	2.35	2.84	3.43	4.14	5.01
40–44	1	1.09	1.31	1.57	1.88	2.25	2.7	3.23	3.87	4.63
45–49	1	1.09	1.28	1.51	1.78	2.1	2.47	2.92	3.44	4.05
50–54	1	1.08	1.25	1.46	1.7	1.97	2.29	2.66	3.1	3.6
55–59	1	1.07	1.23	1.41	1.62	1.86	2.13	2.45	2.81	3.23
60–64	1	1.06	1.2	1.36	1.54	1.75	1.98	2.24	2.54	2.87
65–69	1	1.06	1.18	1.32	1.48	1.65	1.85	2.06	2.31	2.58
70–74	1	1.05	1.16	1.28	1.42	1.56	1.73	1.91	2.11	2.33
75–79	1	1.04	1.14	1.24	1.35	1.47	1.6	1.75	1.91	2.08
80–84	1	1.03	1.09	1.16	1.23	1.3	1.38	1.46	1.55	1.65
85–89	1	1.03	1.09	1.16	1.23	1.3	1.38	1.46	1.55	1.65
90–94	1	1.03	1.09	1.16	1.23	1.3	1.38	1.46	1.55	1.65
95	1	1.03	1.09	1.16	1.23	1.3	1.38	1.46	1.55	1.65
Relative risks of processed meat intake on Colorectal Cancer[e]										
0–24	1	1	1	1	1	1	1	1	1	1
25–95	1	1.03	1.08	1.13	1.19	1.25	1.31	1.38	1.45	1.52
Relative risks of processed meat intake on Breast cancer, Esophageal cancer, Lung cancer, Oral cancer, Stroke, COPD[f]										
0–95	1	1	1	1	1	1	1	1	1	1

[a] In this table rounded to two decimal points.
[b] All-cause mortality: the original relative risks and its 95% Confidence Intervals per 50 g/day were 1.18 (1.11–1.25); data source: Rohrmann et al. (2013).
[c] IHD: the original relative risks and its 95% Confidence Intervals per 50 g/day were 2.568 (1.047–4.657) for age 25–29, 2.124 (1.038–3.478) for age 30–34, 1.720 (1.028–2.489) for age 35–39, 1.545 (1.022–2.093) for age 40–44; 1.547 (1.022–2.097) for age 50–54, 1.520 (1.022–2.037) for age 50–54, 1.467 (1.020–1.922) for age 55–59, 1.422 (1.018–1.826) for age 60–64, 1.386 (1.017–1.75) for age 65–69, 1.354 (1.016–1.683) for age 70–74, 1.325 (1.015–1.622) for age 75–79, 1.252 (1.012–1.475) for age 80–84, 1.252 (1.012–1.475) for age 85–89, 1.252 (1.012–1.475) for age 90–94, 1.252 (1.012–1.475) for age 95 +; data source: GBD 2016 Risk Factor Collaborators (2017).
[d] Diabetes: the original relative risks and its 95% Confidence Intervals per 50 g/day were 1.940 (1.395–2.545) for age 25–29, 1.913 (1.386–2.496) for age 30–34, 1.881 (1.375–2.439) for age 35–39, 1.824 (1.354–2.337) for age 40–44, 1.731 (1.319–2.173) for age 45–49, 1.653 (1.289–2.038) for age 50–54, 1.583 (1.261–1.918) for age 55–59, 1.512 (1.233–1.798) for age 60–64, 1.450 (1.207–1.696) for age 65–69, 1.393 (1.183–1.603) for age 70–74, 1.332 (1.157–1.505) for age 75–79, 1.216 (1.105–1.323) for age 80–84, 1.216 (1.105–1.323) for age 85–89, 1.216 (1.105–1.323) for age 90–94, 1.216 (1.105–1.323) for age 95 +; data source: GBD 2016 Risk Factor Collaborators (2017).
[e] Colorectal Cancer: the original relative risks and its 95% Confidence Intervals per 50 g/day were 1.179 (1.093–1.267) for age 25–95; +; data source: GBD 2016 Risk Factor Collaborators (2017).
[f] We assumed no association between processed meat intake and breast cancer, esophageal cancer, lung cancer, oral cancer, stroke and COPD.

be explained by the distinct initial processed meat intake as well as distinct initial prevalence, incidence and mortality profiles of the modeled diseases.

4.2. Discussion of the main findings

In our minimum-risk-exposure-scenario, approximately 268,700 male deaths and 108,200 female deaths are averted after 10 years of simulation. This estimation is roughly in line with the results in a study using data from the EPIC study, which indicated that 3.3% of deaths could be prevented if all participants had a processed meat consumption of < 20 g/day (Rohrmann et al., 2013). Considering the German population size of 82.4 million and a mortality rate of 11.6 per 1000 population, this translates into approximately 32,000 prevented deaths annually, summing to 320,000 prevented deaths after 10 years. At the same time, the GBD study 2016 (GBD 2016 Risk Factor Collaborators,

Table 3
Number of prevalent disease cases (with 95% Confidence Intervals) and population prevalence in Germany, in projection year 10.

Scenario[a]	IHD				Diabetes				Colorectal cancer			
	Prevalent cases (in thousands)	Prevalence	Prevented cases[b]	% of MRE[c]	Prevalent cases (in thousands)	Prevalence	Prevented cases[b]	% of MRE[c]	Prevalent cases (in thousands)	Prevalence	Prevented cases[b]	% of MRE[c]
Males												
Ref	2050.9	5.19	–	–	1814.9	4.59	–	–	286.4	0.72	–	–
Sc1	2042.5 (2031.4–2059.5)	5.17	−8400	3.42	1805.4 (1795.4–1821.4)	4.57	−9500	3.54	285.9 (284.8–287.2)	0.72	−500	2.84
Sc2	2029.6 (2016.6–2044.8)	5.13	−21,300	8.66	1792.2 (1779.3–1805.0)	4.53	−22,700	8.46	284.9 (283.8–286.3)	0.72	−1500	8.52
Sc3	2012.9 (2002.5–2032.5)	5.09	−38,000	15.45	1773.0 (1762.3–1788.5)	4.48	−41,900	15.61	283.8 (282.7–285.6)	0.72	−2600	14.77
Sc4	1980.1 (1968.5–2003.4)	5.00	−70,800	28.79	1737.0 (1727.4–1756.9)	4.39	−77,900	29.02	281.5 (280.3–283.9)	0.71	−4900	27.84
MRE	1805.0 (1773.7–1836.9)	4.54	−245,900	100.00	1546.5 (1521.6–1558.1)	3.89	−268,400	100.00	268.8 (264.3–273.9)	0.68	−17,600	100.00
Females												
Ref	1642.3	4.00	–	–	2098.2	5.12	–	–	248.2	0.61	–	–
Sc1	1637.7 (1629.3–1651.0)	3.99	−4600	5.67	2090.4 (2083.7–2106.0)	5.10	−7800	6.02	247.9 (247.1–249.1)	0.60	−300	4.62
Sc2	1631.0 (1624.9–1646.8)	3.98	−11,300	13.93	2079.6 (2075.2–2097.1)	5.07	−18,600	14.36	247.4 (246.7–248.7)	0.60	−800	12.31
Sc3	1624.8 (1619.0–1641.9)	3.96	−17,500	21.58	2069.7 (2064.8–2088.4)	5.04	−28,500	22.01	246.9 (246.3–248.3)	0.60	−1300	20.00
Sc4	1612.4 (1608.1–1631.3)	3.93	−29,900	36.87	2049.3 (2046.5–2070.7)	4.99	−48,900	37.76	245.9 (245.3–247.6)	0.60	−2300	35.38
MRE	1561.2 (1531.8–1572.8)	3.80	−81,100	100.00	1968.7 (1933.6–1959.4)	4.79	−129,500	100.00	241.7 (237.9–243.6)	0.59	−6500	100.00

[a] Ref = reference scenario, Sc1 = 4% tax, Sc2 = 11.2% tax, Sc3 = 18.5% tax, Sc4 = 33.3% tax, MRE = minimum-risk-exposure-scenario.
[b] Absolute difference of prevalent cases in respective intervention scenarios compared to reference scenario.
[c] Prevented cases in respective intervention scenarios measured against prevented cases in minimum-risk-exposure-scenario.

Table 4
Population size (with 95% Confidence Intervals) in Germany, in projection year 10.

Scenario[a]	Population size (in thousands)	Prevented deaths[b]	% of MRE[c]
Males			
Ref	39,506.9	–	–
Sc1	39,516.2 (39,476.9–39,562.4)	9300	3.46
Sc2	39,532.3 (39,490.1–39,573.1)	25,400	9.45
Sc3	39,548.7 (39,505.9–39,594.6)	41,800	15.56
Sc4	39,583.6 (39,523.6–39,627.5)	76,700	28.54
MRE	39,775.6 (39,645.7–39,949.9)	268,700	100.00
Females			
Ref	41,006.7	–	–
Sc1	41,011.2 (40,928.5–41,082.9)	4500	4.16
Sc2	41,019.4 (40,948.3–41,097.4)	12,700	11.74
Sc3	41,028.1 (40,947.0–41,103.8)	21,400	19.78
Sc4	41,043.8 (40,963.0–41,115.0)	37,100	34.29
MRE	41,114.9 (41,087.3–41,294.0)	108,200	100.00

[a] Ref = reference scenario, Sc1 = 4% tax, Sc2 = 11.2% tax, Sc3 = 18.5% tax, Sc4 = 33.3% tax, MRE = minimum-risk-exposure-scenario.
[b] Absolute difference of population size in respective intervention scenarios compared to reference scenario.
[c] Prevented deaths in intervention scenarios measured against prevented deaths in minimum-risk-exposure-scenario.

2017) estimated that diets high in processed meat were responsible for an estimated 10,000 deaths in Germany, but solely due to colon and rectum cancers, diabetes mellitus and IHD, and not accounting for all-cause mortality.

4.3. Feasibility and generalizability of the taxes

All four tax scenarios could in principle be transferred to other countries. A modification of the VAT (scenario 2) is straightforward to implement, as it only requires the reclassification of processed meat from a 7% to a 19% VAT level. Previous studies have already modeled extending VAT to additional food categories (Mytton et al., 2007). In contrast to that, a tax on greenhouse gases or a further reaching environmental tax (scenario 1, 3 and 4) is more difficult to implement, as the calculation of accurate tax schemes is complicated. There are a range of other studies that have previously modeled environmental taxes or taxes on greenhouse gases, targeting meat and dairy products overall, not specifically processed and/or red meat, though (Briggs et al., 2013a; Briggs et al., 2016; Edjabou and Smed, 2013; Sall and Gren, 2015). Our minimum-risk-exposure-scenario, with a processed meat intake of < 15 g/day, was used for comparison purposes to estimate the maximum of reducible burden induced by processed meat intake. Nevertheless, processed meat intakes with < 4 g/day have been observed in Iran, Korea and China (Micha et al., 2017).

The German European Prospective Investigation into Cancer and Nutrition (EPIC) cohort showed the highest sausage consumption among all EPIC cohorts (Linseisen et al., 2002). Similarly, in a systematic analysis of nutrition surveys, processed meat intake in Germany was, with an intake of 36 g/day, above the regional average of Western Europe, with an intake of 26 g/day, but similar to the United States of America, with an intake of 36 g/day. Intake was highest in Central Latin America, with an intake of 44 g/day (Micha et al., 2015). This highlights the relevance not only for Germany, but also for other countries.

4.4. Strengths and limitations

This is the first study that hypothesizes realistic and currently-discussed policies in the form of potential taxes on processed meat and examines the impacts on population health using dynamic modeling in Germany. DYNAMO-HIA is a well-established model for quantitative health impact assessment and has been used for similar health impact

assessments of population-level policies, e.g. taxation of alcohol (Lhachimi et al., 2012a), smoking and second-hand-smoking (Fischer and Kraemer, 2016; Holm et al., 2014; Kulik et al., 2012; Lhachimi et al., 2012b), obesity (Lhachimi et al., 2013), or salt intake (Erkoyun et al., 2016; Hendriksen et al., 2015).

Limitations stem from the accuracy of input data. Although the respective input data are the best available to our knowledge and the PSA suggests that uncertainty around our key input parameter do not change our results, the following constraints need to be discussed.

Firstly, there is no generally agreed definition of processed meat, and the term is therefore used inconsistently in epidemiological studies (World Cancer Research Fund, American Institute for Cancer Research, 2007). Our estimates of mean processed meat intake (~30 g/day for females and ~60 g/day for males) are lower than those from the EPIC study (> 40 g/day for females and > 80 g/day for males) (Linseisen et al., 2002), but higher than those found in a systematic analysis of nutrition surveys (~32 g/day for females and ~39 g/day for males) (Micha et al., 2015). Nevertheless, we believe the NVS II is the most recent nationally representative data for processed meat intake.

Secondly, the elasticities for processed meat calculated in our analysis (−0.699, 95% CI −0.756 to −0.642) are in line with those from previous studies considering a two-stage budgeting process, in which the elasticities for meat ranged between −0.48 and −0.92 (see Supplemental Table 11). However, we were not able to differentiate price effects by sex or age. This was due to the fact that the consumer panel data are collected at household level instead of individual level. Other modeling studies, e.g. on sugar-sweetened beverage (SSB) taxation (Manyema et al., 2014), have already faced similar problems and have therefore, like us, applied the same price elasticities for both men and women, and for all age groups.

Thirdly, we used relative risks from the GBD study (GBD 2016 Risk Factor Collaborators, 2017) on IHD, diabetes and colorectal cancer, which have recently been confirmed by a follow up (Micha et al., 2017). We assumed a log-linear relationship between exposure and risk. Based on this assumption, our model assumes that risk will grow exponentially with intake. If, in contrast, there is a threshold effect above a certain level, we may overestimate the positive health effects in higher intake categories. However, our right-tailed intake curve indicates that this would affect relatively few people.

We were not able to examine differential health impacts of processed meat taxation by income groups due to insufficient data. There is, nonetheless, evidence that respective price interventions are likely to reduce inequalities between socioeconomic groups (McGill et al., 2015).

Finally, our cross-price elasticities indicate that a 10% price increase of processed meat results not only in a 6.99% decrease in processed meat demand, but also in an increase of red and white meat as well as a decrease of fish demand. The change in demand for white and red meat is relatively small, with a 0.27% increase of white meat and a 0.31% increase of red meat per 10% price increase of processed meat. The intake of white meat does not have an impact on all-cause mortality (Abete et al., 2014; Larsson and Orsini, 2014; Rohrmann et al., 2013); and in the case of unprocessed red meat, possible harms and benefits are still being debated (Abete et al., 2014; IARC Working Group on the Evaluation of Carcinogenic Risks to Humans, 2018; Larsson and Orsini, 2014; McAfee et al., 2010; Rohrmann et al., 2013; Schwingshackl et al., 2017; Williams, 2007). Therefore, we assume this substitution to have a negligible impact on disease burden and mortality. The accompanied change in demand for fish with a 1.61% decrease per 10% price increase of processed meat is slightly higher. This negative effect can, to a large extent, be attributed to the income effect. This is shown in the Hicksian cross-price elasticities which reflect the income-compensated responses of households. As Supplemental Table 12 shows, the negative cross-price effect decreases from −0.161 to a negligible value of −0.01. Since fish is a relatively expensive product, it is plausible that households will particularly restrict the consumption of this food group. Fish intake seems to have a protective effect on all-cause mortality, with a reduction by 7% per 100 g intake (Schwingshackl et al., 2017). Further research needs to examine to what extent this increase of deaths due to decreased fish consumption would outweigh lives saved from the reduced consumption of processed meat as well as examine the cross-price effect on other food groups.

5. Conclusion

A considerable amount of disease burden has been attributed to processed meat intake and it was recommended to limit its intake. We assessed to what extent the taxation of processed meat, a feasible policy measure, can potentially improve population health outcomes due to tax-induced processed meat intake reduction. There is, however, an opposing trend due to decreased fish intake, which is accompanied by a price increase for processed meat. Further research needs to examine to what extent this increase of deaths due to decreased fish consumption would outweigh lives saved from the reduced consumption of processed meat. We hope to further the discussion on fiscal policies regarding measures for reducing processed meat intake.

Author contributions

SKL had the original idea for the topic. JS and SKL conceived and designed the study. JS, ST and SKL identified data. ST ran analyses on price elasticities. JS ran analyses on health impacts. JS, ST and SKL interpreted results. All authors reviewed several versions of the manuscript critically and have approved the submitted manuscript.

Conflict of interest statement

The authors declare no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ypmed.2018.11.011.

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