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Mitigation potential and global health impacts from emissions pricing of food commodities

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The projected rise in food-related greenhouse gas emissions could seriously impede efforts to limit global warming to acceptable levels. Despite that, food production and consumption have long been excluded from climate policies, in part due to concerns about the potential impact on food security. Using a coupled agriculture and health modelling framework, we show that the global climate change mitigation potential of emissions pricing of food commodities could be substantial, and that levying greenhouse gas taxes on food commodities could, if appropriately designed, be a health-promoting climate policy in high-income countries, as well as in most low- and middle-income countries. Sparing food groups known to be beneficial for health from taxation, selectively compensating for income losses associated with tax-related price increases, and using a portion of tax revenues for health promotion are potential policy options that could help avert most of the negative health impacts experienced by vulnerable groups, whilst still promoting changes towards diets which are more environmentally sustainable.

The food system is responsible for more than a quarter of all greenhouse gas (GHG) emissions, most of which are related to livestock[1–3]. Population growth and dietary changes towards emissions-intensive animal-based foods, in particular in developing countries, are expected to increase the GHG emissions from food and agriculture by up to 80% by mid-century[4–8]. In 2050, food-related GHG emissions could take up half of the total emissions allowed to keep global warming below 2 °C (ref. 8), and exceed this figure by 2070[5]. Thus, reducing the GHG emissions related to food production will have to become a critical component of policies aimed at mitigating climate change[4,9].

Agriculture has long been excluded from comprehensive climate policies due to difficulties in monitoring agricultural emissions[10–12], the lack of technical mitigation options[13,14], and concerns about the potential impacts on food security[15,16], among others. Pricing GHG emissions at source, as is usually envisaged for climate policies covering the energy sector, incentivizes emissions reductions across the life cycle, but would require detailed farm-level measurements—for example of methane emissions from enteric fermentation in the digestive tract of ruminants[10], and of nitrous oxide emissions from agricultural soils treated with nitrogen fertilizers[11,12]. Such non-point sources of emissions are highly variable, and therefore very costly to monitor[13]. And although some technological mitigation options exist[14], most of the agricultural GHG emissions are related to intrinsic characteristics of the agricultural system (such as methane emissions from ruminants and nitrous oxide emissions from fertilizers), and therefore difficult to address without substantial effects on agricultural output and the availability of food[15,16].

Demand-side policies could be a viable option for addressing the environmental costs associated with food production. Levying GHG taxes on the consumption side instead of the production side has been argued to be an economically preferable approach, given the nature of agriculture described above[17,18]. In addition, measures to change diets away from emissions-intensive food commodities, such as meat and dairy, towards more plant-based diets are seen to offer great potential for reducing GHG emissions[4–8,19,20], and could be associated with additional co-benefits in terms of improvements in human health[6,8], something policymakers are increasingly becoming aware of[21,22].

What remains unclear is the scale of changes in food demand and the associated emissions reductions that could result from pricing food-related GHG emissions, as well as the implications that such emissions pricing and the associated increases in food prices could have for food and nutrition security. Previous analyses have focused on specific regions, in particular in high-income settings such as the EU[18] and the UK[23], and global studies that discussed the implications of climate policies for food security did not include an explicit analysis of health outcomes, but framed food security in terms of changes in caloric availability[15,16]. We address this research gap by coupling an environmental–economic analysis of GHG taxation of food commodities to a consistent health modelling framework, and by extending the analysis to all major world regions, including low-, middle-, and high-income countries.

Here we present what we believe is the first global analysis of the impacts that levying GHG taxes on food commodities could have on GHG emissions and human health. We used an agriculture–economic model, the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT), to project future food consumption for 62 agricultural commodities in over 150 world regions[24]. Our model scenarios focus on the year 2020, the year in which a new global climate agreement is to be ratified. Our analysis accounts for price-mediated changes in the consumption of particular commodities, as well as the effects of price changes on substitution across food groups (for example, replacing beef

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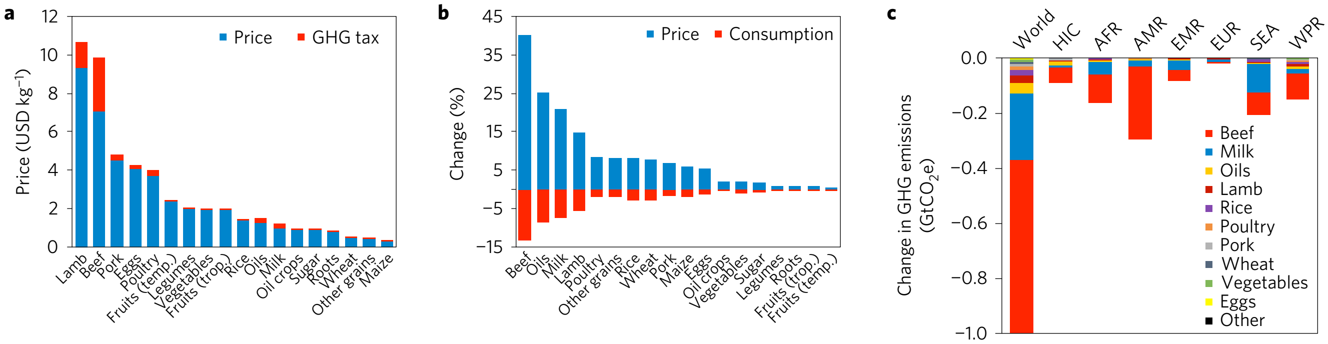

Figure 1 | Impacts of GHG taxes on food prices, consumption, and GHG emissions. a, Prices and GHG taxes (in US dollars per kg) by food commodity. **b**, Percentage changes in prices and consumption by food commodity. **c**, Change in GHG emissions (in $GtCO_2e$) by food commodity and region. Regions include high-income countries (HIC), and the low- and middle-income countries of Africa (AFR), America (AMR), the Eastern Mediterranean (EMR), Europe (EUR), South-East Asia (SEA), and the Western Pacific (WPR), and an aggregate of all regions (World). Impacts are for a tax scenario in which GHG taxes are levied on all food commodities (TAX).

consumption with poultry). It also takes into account the impacts that tax-related changes in income have on consumption. We assumed taxes are implemented independently in each country (that is, the result for each country shows the impact if the carbon pricing was implemented in that country only), and that production in each country adjusts to internal changes in demand. As our focus is on the demand side, we did not explicitly track the induced changes in world prices, trade, or agricultural production in other countries.

We used a database of life-cycle analyses to quantify the emissions related to food production[6,25], and to calculate GHG taxes on food commodities corresponding to their emissions intensities, differentiated by region and food group, and an emissions price based on estimates of the social cost of carbon[26]. In our main analysis, we adopted an emissions price of \$52 tCO_2e^{-1} (US dollars per metric tonne of CO_2 equivalents), which corresponds to calculating the net present value of future climate damages associated with one additional tonne of carbon dioxide equivalent (tCO_2e) using a discount rate of 3%. Several alternative values (\$14, \$78 and \$156 tCO_2e^{-1}) were considered in a sensitivity analysis (see Methods). GHG taxes, which differed by region and food group, were levied as consumption taxes in each region, and therefore covered both imported food commodities and domestically produced commodities that were not exported.

We analysed the implications of emissions pricing of food commodities for food and nutrition security by estimating the health impacts associated with changes in dietary and weight-related risk factors. For that purpose, we used a global comparative risk assessment framework with five disease states and six dietary and weight-related risk factors which has been purpose-built to be used in coupled agriculture–health analyses[8,27]. The disease states were coronary heart disease, stroke, type 2 diabetes mellitus, cancer (which is a combination of site-specific cancers), and an aggregate representing all other disease risks. The dietary risk factors were low fruit and vegetable consumption and high red meat consumption, which together accounted for about half of all deaths that were attributable to diet-related risks in 2013[28]. The weight-related risk factors corresponded to the four classes of underweight, normal weight, overweight, and obesity, which accounted for about a third of all deaths attributable to metabolic risk factors[28]. We adopted disease associations in the form of relative risk estimates from meta-analyses and pooled analyses of prospective cohort studies which identified dose–response relationships with decreased disease risks for fruit and vegetable consumption, and increased disease risks for red meat consumption, obesity, and for most health endpoints also for overweight and underweight (Supplementary Table 6). We used the scenario estimates of total energy intake to assess changes in body weight based on historical relationships between weight categories and caloric availability[27], and we adjusted the availability of different food commodities used in the health analysis for waste at the consumption level using international estimates (Supplementary Table 2)[29]. Our main analysis focused on the health impacts on adults (aged 20 and older), but we analysed the potential impacts of GHG taxation on child undernourishment, something that is closely associated with micronutrient deficiencies, in a sensitivity analysis.

We begin our analysis by estimating the impacts of levying weighted GHG taxes on all food commodities. Motivated by concerns for food and nutrition security, in particular in developing countries, we then exempt health-critical food groups, such as fruits and vegetables and staple crops, from taxation, and we explore tax scenarios focused on animal-based foods, red meat, and beef. In addition, we considered scenario variants in which income losses due to GHG taxes were compensated by other fiscal interventions (for example, by recycling the revenues back to the consumer directly or by increasing public expenditure); and scenario variants in which three-quarters of the GHG tax revenues in each region were used for subsidizing fruit and vegetable consumption by lowering commodity prices. The latter scenarios would leave a portion of revenues available for other uses (for example, for general government spending or saving, and to meet any administrative costs that could be associated with levying GHG taxes on food commodities). We present our main results for countries grouped by income and region (Supplementary Table 1), and provide all results for 150 regions in the Supplementary Data File (also available at https://ora.ox.ac.uk/objects/uuid:39e07a40-ceaa-4e1f-82cb-5fb3bf70c7ed).

Effects of levying emissions taxes on food

GHG emissions and the associated GHG taxes varied by commodity and region because of different management practices (for example, extensive production of grass-fed beef in Latin America compared to intensive production of grain-fed beef in parts of the US and mixed beef and dairy systems in Europe; Supplementary Table 3), but differences were greatest between commodities. With a GHG emissions price of \$52 tCO_2e^{-1}, average GHG taxes on food commodities (Fig. 1a and Supplementary Table 7) were highest for animal-sourced foods, such as beef (\$2.8 kg^{-1}), lamb (\$1.3 kg^{-1}), and pork and poultry (\$0.3 kg^{-1} each); intermediate for products, such as vegetable oils (\$0.3 kg^{-1}), milk and eggs (\$0.2 kg^{-1} each), and rice (\$0.1 kg^{-1}); and low (<\$0.1 kg^{-1}) for most other crops, such as fruits, vegetables, grains, roots, legumes and sugar.

Levying GHG taxes on all food commodities resulted in increases in prices and reductions in consumption (Fig. 1b and Supplementary Tables 8 and 9) that were high (15–40% for prices; 6–13% for

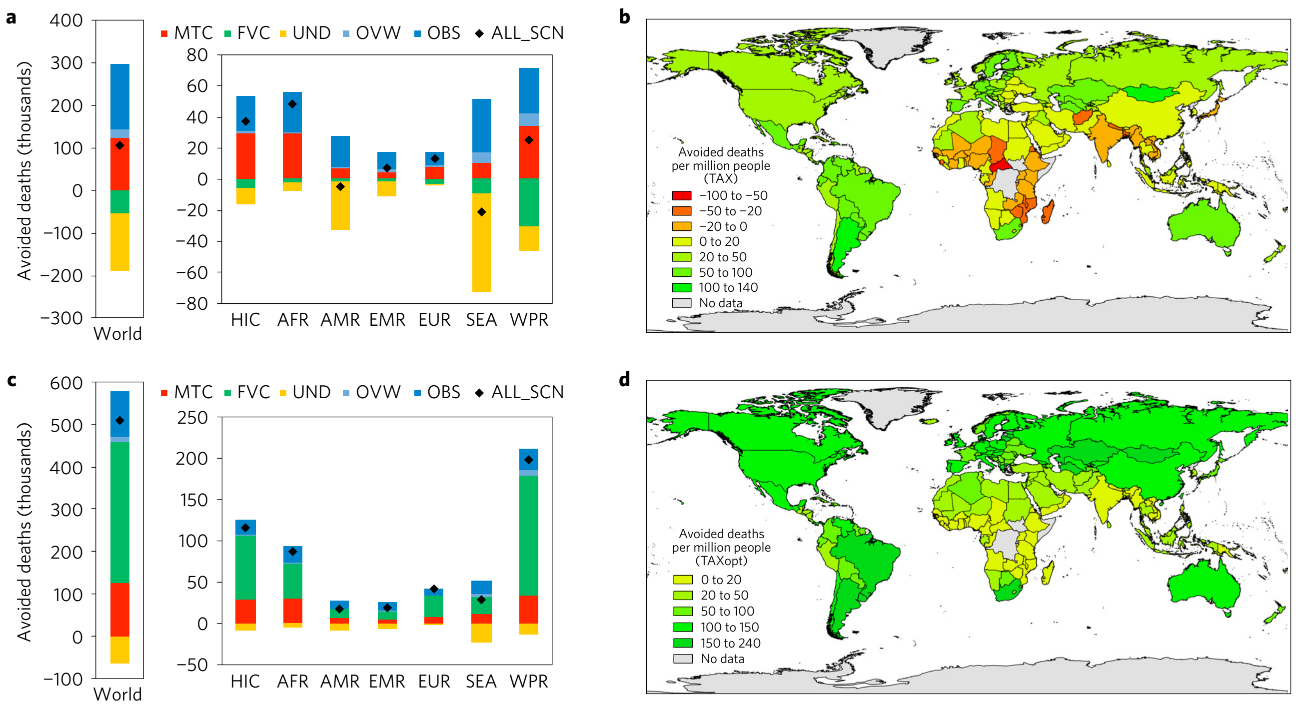

Figure 2 | Regional health impacts of levying GHG taxes on food commodities. a–d, Avoided deaths in thousands (**a**,**c**) and per million people (**b**,**d**) in a scenario that covers all food commodities (TAX; **a**,**b**), and in a regionally optimized combination of tax scenarios (TAXopt; **c**,**d**) that, depending on the region, include exempting health-critical and other food groups from taxation, and using parts of the tax revenues for subsidizing fruit and vegetable consumption. Risk factors (**a**,**c**) include increases in red meat consumption (MTC), decreases in fruit and vegetable consumption (FVC), increases in the prevalence of underweight (UND) and overweight (OVW) people, and increases in obesity (OBS). Decreases in risk factors are associated with positive health impacts (greater number of avoided deaths), whilst increases in risk factors are associated with negative health impacts (displayed as negative values of avoided deaths). ALL_SCN, all scenarios.

consumption) for beef, vegetable oils, milk, and lamb; intermediate (5–9% for prices; 1–3% for consumption) for poultry, the category of 'other grains', rice, wheat, pork, maize, and eggs; and low (<3% for prices; <1% for consumption) for all other food commodities. The percentage changes in meat prices were greater than average in the low- and middle-income countries (LMICs) of the Americas due to high emissions intensities (resulting in high GHG taxes); and they were lower than average in high-income countries and the LMICs of Europe (due to low emissions intensities, resulting in low GHG taxes) and in the LMICs of the Eastern Mediterranean (due to high initial prices). Percentage changes in the price and consumption of vegetable oils which have intermediate emissions intensities were higher, on average, than those of many animal-based products with greater emissions intensities, because of the relatively low reference prices for vegetable oils (Fig. 1a). Absolute changes in calories and grams of food consumed are reported in the Supplementary Information (Supplementary Tables 9 and 10).

Levying GHG taxes on all food commodities resulted in 107,000 avoided deaths (95% confidence interval (CI), 95,000–118,000) globally in 2020 (Fig. 2a), two-thirds of which were due to changes in dietary risk factors, and one-third due to changes in weight-related risk factors. The dietary risk factors were composed of 124,000 (CI, 123,500–125,000) avoided deaths due to reduced red meat consumption, which were partly offset by 54,000 (CI, 51,000–57,000) additional deaths due to less fruit and vegetable consumption, and the weight-related risk factors were composed of 134,000 (CI, 124,000–145,000) additional deaths due to more people being underweight, which were offset by 20,000 (CI, 18,600–22,000) and 151,000 (CI, 147,000–155,000) avoided deaths due to less people being overweight and obese, respectively. The global net total of avoided deaths consisted of 146,000 (CI, 140,000–152,000) avoided deaths in 115 out of 150 world regions, which were offset by 39,000 (CI, 30,000–49,000) additional deaths in 35 world regions, in particular in the LMICs of Africa and South-East Asia (Fig. 2b and Table 1).

The alternative tax scenarios reduced the negative health impacts and increased the benefits (Table 1). Constraining the tax coverage minimized the negative health impacts associated with increases in the prevalence of underweight in the LMICs of Africa and South-East Asia (TAXadj, TAXani, TAXrem, TAXbef), and it led to net positive impacts when paired either with income compensation (which further reduced underweight-related impacts; *_r* scenarios) or with subsidies for fruits and vegetables (which led to additional diet-related health benefits; *_s* scenarios). In contrast, maintaining broad tax coverage maximized the health benefits, in particular those associated with reductions in overweight and obesity, in all other regions (TAX). Compensating income losses had little aggregate impacts in those regions (*_r* scenarios), but using part of the tax revenues to subsidize fruit and vegetable consumption led to substantial additional health benefits (*_s* scenarios). For the latter scenarios, the greater the tax coverage, the greater the tax revenues (Supplementary Tables 19 and 20), the more revenues could be used for subsidizing fruit and vegetable consumption, and the greater the associated health benefits (Table 1).

Allowing each region to adopt the tax scenario that resulted in the greatest health benefits (TAXopt) eliminated the negative health impacts on individual low- and middle-income countries (Table 1 and Fig. 2c,d). At the same time, the global net health benefits increased almost fivefold to 510,000 (CI, 492,000–527,000) avoided deaths. In this scenario, three-quarters of all countries (113 out of 150), including all high-income countries, 88% of middle-income countries, and 30% of low-income countries, adopted the tax scenario with full coverage paired with fruit and vegetable subsidies, and most of the remaining countries adopted scenarios

Table 1 | Mitigation potential and health impacts of levying GHG taxes on food commodities for different tax designs.

Scenario	Emissions reductions (MtCO$_2$e)	Global health impacts (thousands of avoided deaths and number of countries)					Regional health impacts (thousands of avoided deaths)						
		World	Positively affected		Negatively affected		High-income countries	LMICs Americas	LMICs Africa	LMICs Eastern Mediterranean	LMICs Europe	LMICs South-East Asia	LMICs Western Pacific
			abs	count	abs	count							
TAX	−1,003	106.54	145.79	115	−39.26	35	37.14	48.01	−4.45	7.44	13.60	−20.76	25.56
TAXadj	−962	140.13	151.16	125	−11.03	25	38.24	43.70	1.47	6.73	12.44	−3.63	41.19
TAXani	−959	136.55	140.32	132	−3.77	18	36.18	38.67	3.25	5.84	11.30	−0.37	41.70
TAXrem	−689	144.57	145.17	140	−0.61	10	37.16	35.56	4.44	4.82	10.82	8.75	43.03
TAXbef	−657	90.96	91.42	138	−0.45	12	20.84	32.65	3.68	3.73	6.20	7.26	16.61
TAX_r	−970	119.14	148.08	115	−28.94	35	37.46	47.37	−1.31	7.75	13.56	−14.03	28.35
TAXadj_r	−935	148.81	153.14	130	−4.33	20	38.54	43.12	3.84	6.95	12.40	0.79	43.17
TAXani_r	−934	144.47	145.00	141	−0.53	9	36.47	38.12	5.40	6.03	11.26	3.62	43.57
TAXrem_r	−673	148.47	148.49	148	−0.02	2	37.35	35.18	5.83	4.89	10.80	10.11	44.32
TAXbef_r	−645	93.64	93.67	145	−0.03	5	21.00	32.29	4.80	3.79	6.18	8.35	17.24
TAX_s	−952	492.69	499.00	133	−6.31	17	115.81	88.33	9.42	18.47	40.64	22.34	197.67
TAXadj_s	−926	406.05	407.98	142	−1.93	8	101.94	79.79	12.76	15.22	31.81	22.00	142.51
TAXani_s	−925	380.58	380.93	143	−0.35	7	95.23	72.77	14.35	13.87	29.21	22.37	132.78
TAXrem_s	−668	295.15	295.19	148	−0.04	2	70.34	60.15	11.31	8.65	18.92	16.76	109.03
TAXbef_s	−642	189.46	189.49	147	−0.03	3	44.51	55.62	9.40	6.70	11.34	13.62	48.27
TAXopt	−919	509.48	509.48	150	0.00	0	115.81	88.33	18.39	18.99	40.64	29.53	197.78

The health impacts are reported in avoided deaths (in thousands) globally (World), decomposed by positive and negative impacts on individual countries in terms of avoided deaths in thousands (abs) and by number of countries (count), and avoided deaths in thousands by regional aggregates, including high-income countries, and low and middle-income countries (LMICs) in different regions. The tax scenarios include scenarios that cover all commodities (TAX), exclude fruit and vegetables, staples, and legumes from taxation (TAXadj), focus on animal-based foods (meats, eggs, milk) (TAXani), focus on red meat (beef, lamb, pork) (TAXrem), focus on beef (TAXbef), and scenario variants in which income losses are compensated (_r scenarios), and variants in which three-quarters of tax revenues are used to subsidize fruit and vegetable consumption (_s scenarios). Regionally optimized combination of tax scenarios (TAXopt).

with constrained coverage paired either with fruit and vegetable subsidies or with income compensation (Supplementary Table 13).

Global food-related GHG emissions were reduced by 1.0 GtCO$_2$e (9.3%) under full tax coverage, and by 919 MtCO$_2$e (8.6%) in the regionally optimized tax scenario (Fig. 1c and Supplementary Tables 14–17). About two-thirds of the emissions reductions were due to reduced consumption of beef (632–633 MtCO$_2$e), one-quarter due to reduced milk consumption (222–240 MtCO$_2$e), with greater reductions under full coverage than under the regionally optimal tax combination or more constrained tax designs (Supplementary Table 18). Other changes in consumption patterns made smaller contributions. Across regions, emissions reductions ranged from 15–17 MtCO$_2$e (3%) in the LMICs of Europe to 286–294 MtCO$_2$e (16%) in the LMICs of the Americas. About three-quarters (733–775 MtCO$_2$e) of all emissions reductions occurred in middle-income countries, 12–14% (109–139 MtCO$_2$e) in low-income countries, and 8–9% (78–89 MtCO$_2$e) in high-income countries.

Our findings in context

Our analysis suggests that levying GHG taxes on food commodities could, if appropriately designed, be a health-promoting climate-change-mitigation policy in high-income, middle-income, and most low-income countries (except possibly for some very low-income countries in Sub-Saharan Africa; Supplementary Table 23). Contrary to concerns that increased food prices and reductions in food availability would negatively impact food and nutrition security[15,16], we found that the health benefits from tax-related reductions in obesity could outweigh the health losses from increased numbers of underweight people in three-quarters of all regions, and that tax-related reductions in red meat consumption would confer additional health benefits that outweigh health losses from reductions in the consumption of other food groups. However, special policy attention would be needed in some low-income countries, other countries where a high fraction of the population is underweight, and possibly for low-income segments within countries, to avert potential health losses associated with increased numbers of people who are underweight and, to a lesser extent, with reduced consumption of fruits and vegetables. Sparing food groups known to be particularly beneficial for health from taxation, compensating income losses associated with tax-related price increases, and using a portion of tax revenues for health promotion are potential policy options that could help avert the negative health impacts for exposed populations, whilst promoting changes towards diets which are more environmentally sustainable.

Potential synergies exist with other climate change mitigation options and food-related health policies. The climate change mitigation potential identified in this study is about 1 GtCO$_2$e, more than the current emissions of global aviation[30]. It represents a 9% reduction in food-related GHG emissions in 2020, and about 10% of the emissions gap in 2020 that needs to be bridged to have a likely chance of limiting global warming to below 2 °C (ref. 31). The identified mitigation potential compares favourably to that of many technical supply-side measures in the agricultural sector, such as rice, livestock and manure management (each below 250 MtCO$_2$e, but above 2 GtCO$_2$e when combined with cropland and soil management)[32,33], and could therefore contribute significantly to emissions-reduction targets for agriculture[34].

The health benefits identified in this study (100,000–500,000 avoided deaths globally) are of an order of magnitude similar to the potential health benefits that global climate policies could have on air pollution associated with coal-fired power generation (estimated at 500,000 ± 200,000 avoided premature deaths per year by 2030)[35]. However, the health benefits are small when compared to overall mortality (representing a reduction of less than 1% in most regions) and to the potential health benefits of dietary change towards more plant-based diets (estimated at 5–8 million avoided deaths in 2050)[8]. Thus, additional policy measures would be needed to realize a greater fraction of the potential health and climate change benefits associated with dietary change[36].

As a first global analysis of the combined health and emissions impacts of levying GHG taxes on food commodities, our study has several limitations which could be addressed by further research. Our health analysis focused on changes in energy intake and consumption at the level of food groups. This focus is due to the strength of epidemiological evidence regarding those risk factors, but it does not take into account changes in the nutritional quality of diets, such as the composition of fatty acids, sodium content, and levels of micronutrients. Better regionally comparable data would be needed to study the influences of such risk factors at a global level. In a sensitivity analysis, we analysed the potential impacts of GHG taxes on child undernourishment and stunting, both of which are strongly correlated with micronutrient deficiencies among children[37], without identifying changes that would alter our conclusions (see Methods). Although our main health analysis was limited to changes in fruit and vegetable consumption, red meat consumption, and body weight associated with changes in energy intake, those risk factors were responsible for about a third of all attributable deaths in 2013[28], and for the majority of diet- and weight-related deaths that can be linked to dietary changes[28].

Our environmental analysis focused on changes in GHG emissions. Although we used the latest available literature values of regionally comparable emissions intensities, those did not account for all climate–carbon feedbacks, in particular for methane[38]. Including such feedbacks would increase methane's global warming potential (from 25 to 28) and result in greater emissions estimates, in particular for methane-intensive foods, such as beef, milk, and to a lesser degree, rice[25]. We also did not analyse any secondary economic feedback effects, such as changes in GHG emissions from the health sectors that could be associated with changes in disease incidence[39], nor did we analyse other potential environmental benefits, such as lower emissions of nitrogen to water bodies and reduced land-use change that could be associated with tax-related dietary changes away from emissions-intensive animal-based foods[4,6].

Our economic analysis used a comparative static framework and focused on regionally comparable impacts per country based on global data sets. Using a comparative static framework allowed for a transparent analysis, but it did not account for market adjustments in future years, or potential time lags between the introduction of GHG taxes and changes in food consumption and subsequent health outcomes. Because we relied on global agricultural data, we were not able to resolve food processing in sufficient detail (other than for vegetable oils and animal feed) on a regionally comparable basis. Instead we focused on primary commodities as targets for GHG taxation, something that implicitly assumes that mark-ups from GHG taxes are passed through to the consumer. In terms of regional detail, the use of global data sets enabled a regionally comparative analysis that accounted for inequality between countries, but it did not allow us to study the potential impacts that GHG taxation of food commodities could have on food inequality within countries. Analyses of the latter might expose similar issues of differentiated impacts and potential avenues for compensation as at the international level. We encourage the compilation of more detailed databases, and the pursuit of case studies in countries and regions where sufficient data exist to quantify the impacts of GHG taxation on processed foods, regional inequality, and agricultural incomes. At the global level, an important research question remains as to what impacts food-related GHG taxation in one country, or group of countries, could have on other countries and on international food markets. We hope our comparative regional analysis provides a good starting point for such research.

Methods

Methods and any associated references are available in the online version of the paper.

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Author contributions

M.S. designed the study and conducted the initial analysis. M.S., P.S., D.M.-D'C. and S.R. contributed model components. M.S. wrote the manuscript, with contributions from H.C.J.G. All authors analysed the results and commented on the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to M.S.

Competing financial interests

The authors declare no competing financial interests.

Methods

We used a coupled modelling framework that represents agricultural, economic, environmental and health aspects of the food system to analyse the environmental and health impacts of levying GHG taxes on food commodities. In our agricultural analysis, we used the IMPACT global agricultural model to project future food consumption for 62 agricultural commodities in more than 150 world regions[24]. The IMPACT model is based on a global partial equilibrium multi-market model of agricultural production, demand, trade and prices. The multi-market model simulates the operation of national and global markets for agricultural commodities, solving for equilibrium prices and quantities, subject to biophysical constraints (water, yields) and macroeconomic trends (population, economic growth) (Supplementary Methods 1). For calibrating the model in the base year, a cross-entropy method was used to produce a consistent and balanced data set, based on global agricultural data obtained from food balance sheets of the Food and Agriculture Organization (FAO) of the United Nations[24].

In our economic analysis, we estimated the impacts that levying GHG taxes on food commodities could have on food consumption, by using international data on commodity prices and region-specific estimates of demand elasticities. Both price and elasticity data were adopted from IMPACT, and we used its demand system for the analysis of demand changes as a result of tax-related changes in consumer prices (Supplementary Methods 1). Our analysis includes own-price, cross-price, and income effects. In our analysis of income effects, we used gross domestic product (GDP) per capita adjusted for purchasing power parity as proxy for income, and we assumed that changes in income are equivalent to tax revenues. All monetary data were converted to the value of the US dollar in 2010 by using changes in the consumer price index by region, based on data from the International Monetary Fund.

For calculating levels of GHG taxes that would internalize the climate-change-related costs of food consumption we used commodity-specific emissions factors (to estimate food-related GHG emissions) and estimates of the social cost of carbon (to estimate the tax levels). We adopted the emissions factors for livestock from a global life-cycle assessment with regional detail undertaken by the FAO (Supplementary Table 3)[25]. The assessment included all main emissions sources along the food supply chain from the farm gate to the retail point, including land use, feed production, animal production, processing, and transport, including international trade. Emissions factors for non-animal products were adopted from a comprehensive meta-analysis of life-cycle assessments including 555 estimates (Supplementary Table 4)[6]. We resolved 18 food groups in our analysis (beef, lamb, pork, poultry, milk, eggs, vegetable oils, oil crops, sugar, vegetables, temperate fruits, tropical fruits, wheat, maize, rice, other grains, legumes, roots). We did not account for GHG emissions related to the consumption of fish and seafood, because those food groups were not resolved in the projections of food demand used in this study[24].

In our health analysis, we used a global comparative risk assessment framework designed for coupled agriculture–health analyses[8,27]. We estimated the mortality and disease burden attributable to dietary and weight-related risk factors by calculating population impact fractions (PIFs) which represent the proportions of disease cases that would be avoided when the risk exposure was changed from a baseline to a counterfactual (Supplementary Methods 2)[28,40,41]. The relative risk estimates used in those calculations were adopted from pooled analyses of prospective cohort studies[42,43], and from meta-analysis of prospective cohort and case-control studies (Supplementary Table 6)[44–51]. Mortality data were taken from the Global Burden of Disease project[52], and projected forward by using data from the UN Population Division[53]. We accounted for the uncertainty related to the relative risk parameters in our mortality estimates. We approximated the error distribution of relative risks by a normal distribution, which is justified for the magnitude of errors dealt with here (<50%) (see, for example, IPCC Uncertainty Guidelines). We then used standard methods of error propagation to calculate the uncertainty intervals associated with diet- and weight-related changes in mortality.

Sensitivity analysis. In the sensitivity analyses, we estimated the health impacts on children using different models, and we calculated, as additional health indicators, the numbers of life years (YLS) and disability-adjusted life years (DALYs) saved.

Our main analysis focused on the mortality impacts for adults (aged 20 and older). In a sensitivity analysis, we estimated the potential impacts of food-related GHG taxation on undernourishment and stunting amongst children (aged five and younger) using a model that resolves the food and non-food (socio-economic) causes of undernourishment and stunting (Supplementary Methods 2)[54,56]. We estimated that tax-related increases in undernourishment and stunting amongst children could lead to 3,200 (CI, 2,900–3,500) additional deaths in the standard tax scenario, and to about 1,700 (CI, 1,400–2,000) additional deaths in the regionally optimized tax scenarios (Supplementary Table 21). The global health benefits were reduced by 3% in the former, and by less than 0.5% in the latter, without reversing any health impacts on the regional or country level.

In our main analysis, we focused on mortality as our primary health outcome. In a sensitivity analysis, we estimated the impacts of tax-induced consumption changes on several other health metrics, including premature deaths—that is, deaths before the age of 70; years of life lost, a measure that gives greater weight to years of life lost early in life; and DALYs lost, which, in addition to mortality, factors in the impacts of different diseases on the quality of life. For calculating the years of life lost, we multiplied each age-specific death by the life expectancy expected at that age using the Global Burden of Disease standard abridged life table[55], and for calculating DALYs, we used region- and age-specific mortality–DALY ratios calculated from World Health Organization (WHO) estimates for the year 2012. Each of the different metrics led to qualitatively similar results at the regional level, but the metrics also identified a greater number of countries (up to eight low-income countries in Sub-Saharan Africa in the regionally optimized scenario) that could be negatively impacted by levying GHG taxes on food commodities (Supplementary Tables 22 and 23).

We conducted other sensitivity analyses in which we varied the proportion of tax revenues used for subsidizing fruit and vegetable consumption, and in which we used different GHG prices corresponding to different assumptions about the discount rate used to calculate the net present value of future climate damages[26,57]. Using less revenues for subsidizing fruit and vegetable consumption or using a lower GHG price led to smaller global health benefit, whilst using more revenues and higher GHG prices led to greater benefits, in each case preserving their relative regional distribution (Supplementary Tables 24–26).

Our main analysis accounted for epidemiological uncertainty related to the relative risk estimates used. In a final sensitivity analysis, we explored the uncertainty related to the environmental and economic parameters used in our analysis. For the uncertainty related to price responses, we used a confidence interval of ±10% around the mean, based on a meta-analysis of price elasticities[58], and for the uncertainty related to emissions intensities, we used confidence intervals of 50% for ruminants and 30% for other commodities, based on case studies on the country level[25]. The relative health and environmental impacts of GHG taxation were preserved in each analysis, and we did not observe any reversal of health impacts on the regional or country level (Supplementary Tables 25, 27 and 28).

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