Carbon pricing of food in Australia: an analysis of the health, environmental and public finance impacts

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Abstract

Objective: To estimate the impact of integrating the price of greenhouse gas emissions into the price of food commodities on dietary and weight-related risk factors and associated disease burden in Australia, as well as on national emissions reductions and public revenues.

Methods: We used country-specific data for Australia to build a coupled modelling framework that includes economic, environmental and health analyses. Data sources included the 2011-12 Australian food and nutrition survey, meta-analysis of food-related lifecycle emissions, and price and income elasticities. Consumption-related changes in disease burden were calculated using a comparative risk assessment framework with 11 disease states and seven diet and weight-related risk factors.

Results: Including a price of $23 per tonne of carbon dioxide equivalent (tCO2-eq) – the starting price of the former Australian carbon pricing mechanism – into the price of food commodities in our model simulations led to 49,500 avoided disability-adjusted life years (DALYs) (95% confidence interval [CI] 43,200-55,200). Food-related greenhouse gas emissions were reduced by 6% (2.3 MtCO2-eq), and greenhouse gas tax revenues amounted to $866 million.

Conclusion: Incorporating the price of food-related greenhouse gas emissions into the price of food commodities in Australia could be beneficial for population health, while generating public finance revenues and supporting Australia's emission-reduction commitment.

Implications for public health: Climate policies that integrate the price of greenhouse gas emissions into the price of food commodities in Australia are compatible with public health objectives to reduce diet-related disease mortality.

Key words: carbon tax, comparative risk assessment, climate policy and public health

As part of a new global agreement to prevent dangerous levels of climate change, Australia has agreed to reduce national greenhouse gas (GHG) emissions by 26–28% by 2030, compared to 2005 levels.[1] For emissions reductions to be achieved cost-effectively, international organisations have recommended the use of market-based approaches to pricing GHG emissions, such as GHG taxes or emissions trading schemes.[2–5] While Australia had implemented a carbon pricing mechanism in 2012, it lacked broad political support and was repealed in 2014. Although different policy instruments can be used to reduce GHG emissions,[6] most climate change experts and political parties agree that pricing GHG emissions – either implicitly, using fuel taxes and emissions standards (as is current practice), or explicitly, via an emissions tax or emissions trading scheme – is a crucial component for achieving Australia's climate change commitment.

In Australia, the potential impact of implementing a price on GHG emissions has been assessed from environmental and economic perspectives.[7,8] However, the potential impact on health has not been studied. Pricing GHG emissions can affect health in various ways. Those include impacts from averted climate change effects, such as heat stress and the exposure to droughts and floods,[9] and impacts on respiratory health due to lower concentrations of particulate matter from coal-fired power plants.[10,11] The former Australian Carbon Pricing Mechanism did not cover the GHG emissions associated with food production; however, extending GHG emissions pricing to food commodities could also have an effect on diet-related diseases that would result from changes in food consumption.[12,13]

Dietary risks and high body mass index were the two leading risk factors for disease burden in Australia in 2010 and 2013.[14,15] Integrating the price of GHG emissions into the price of food commodities would increase the cost of emissions-intensive foods, such as meat, fish and dairy, which – in turn – would reduce demand for those commodities.[12] The associated changes in diet-related risk factors, such as high intake of red and processed meat, low intake of fruits and vegetables, and excessive total energy intake related to overweight and obesity, have implications for diet and weight-related poor health.[15–21]

This paper aims to estimate the health impacts that would result from changes in dietary and weight-related risk factors as a consequence of including the cost of food-related GHG emissions in the price of food commodities in Australia.

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For contextualisation, we also estimate the contribution that GHG pricing of food commodities could have on reducing GHG emissions, as well as the potential tax revenues that could be generated by pricing food-related GHG emissions. The former Australian Carbon Pricing Mechanism did not cover the GHG emissions related to food and agriculture. Thus, the guiding question of this study is whether a policy to extend GHG emissions pricing to food commodities should be endorsed from public health, environmental and public finance perspectives.

Methods

We estimated the health, environmental and public finance impacts of integrating the cost of GHG emissions into the price of food commodities in Australia by using a coupled modelling framework that included economic, environmental and health analyses.

In our economic analysis, we estimated how food consumption is affected by changes in the price of food commodities based on their GHG emissions content. Key parameters for the economic analysis were price and expenditure elasticities that determine how food demand changes subject to price and expenditure changes.[22] Despite recent policy interest, there is no robust and comprehensive set of own-price and cross-price elasticities specifically estimated for food in Australia.[23,24] We therefore used a suitable set of food elasticities estimated for the UK population (see Supplementary File item A1).[25] UK-based elasticity parameters have been used in previous studies focused on consumption changes in Australia due to similarities in food consumption and purchasing behaviour.[26]

We applied the elasticity estimates to Australian consumption, expenditure and price data. Data on food consumption, stratified by age group and sex, were adopted from the 2011-12 Australian Health Survey, which reported results from a 24-hour dietary recall on food, beverages and dietary supplements from more than 12,000 participants across Australia.[27] Prices of food commodities were derived as population-weighted average values from a report by the Australian Bureau of Statistics (ABS) on average retail prices in Australian capital cities.[28] Data on food expenditure were taken from the Australian Household Expenditure Survey, 2009-10.[29] We aggregated the consumption and price data to the commodity detail of the elasticity estimates, and we adjusted all prices to 2012 Australian dollars by using the consumer price index.[30] We calculated changes in food expenditure by subtracting GHG tax revenues from baseline food expenditure.

In our policy scenario, we changed the price of food commodities based on their GHG emissions content and on estimates of GHG emissions prices. In our main analysis, we adopted a price of GHG emissions of $23 per tonne of carbon dioxide equivalent (tCO_2-eq), which was the starting price of the Australian Carbon Pricing Mechanism. In a sensitivity analysis, we adopted different GHG prices that represent varying estimates of the social cost of GHG emissions.[31,32] GHG emissions factors were adopted from a recent meta-analysis of lifecycle analyses that estimated the 'cradle to farm gate' emissions of different food items.[33] The factors exclude emissions from land-use change and post-farm-gate activities, such as processing, packaging and transportation to households. The same GHG emissions factors were used in our environmental analysis to calculate the changes on food-related GHG emissions that result from incorporating the price of GHG emission into the price of food commodities.

In our health analysis, we estimated changes in mortality and disease burden measured in disability adjusted life years (DALYs) associated with changes in food consumption by using a comparative risk assessment framework with 11 disease states and seven diet and weight-related risk factors. The disease states included coronary heart disease (CHD), stroke, type 2 diabetes (T2DM), seven diet and weight-related cancers (colon and rectum cancers, mouth and oropharynx cancers, oesophagus cancer, stomach cancer, trachea, bronchus, lung cancers, aggregate cancer) and an aggregate for all other causes. The weight-related risk factors corresponded to the four weight classes of underweight (BMI<18·5), normal weight (18·5<BMI<25) – which is risk-neutral, overweight (25<BMI<30), and obese (BMI>30), and the diet-related risk factors included fruit consumption, vegetable consumption, red meat consumption and processed meat consumption.

We calculated changes in weight-related risk factors by using an empirical relationship between energy intake and weight gain.[34] According to the relationship, a sustained increase in energy intake of 100 kJ per day, assuming no change in physical activity, leads to an increase of 1 kg body weight on average, with half of the weight gain being achieved in one year and 95% in three years.[34] We estimated the changes in the complete weight distribution of Australians by converting changes in weight to changes in mean BMI, and applying those changes to the BMI distribution of Australians, differentiated by age group and sex, holding the shape parameter constant. For estimating the BMI distributions, we used ABS data on the prevalence of overweight, obesity and underweight,[27] and for converting weight changes to changes in BMI, we used ABS estimates of height, differentiated by age group and sex.[27]

We estimated the mortality and DALYs attributable to dietary and weight-related risk factors by calculating population attributable fractions (PAFs). PAFs represent the proportions of disease cases that would be avoided when the risk exposure is changed from a baseline situation (the diet and weight-related risk levels without GHG taxes) to a counterfactual situation (the diet and weight-related risk levels with GHG taxes on food commodities), see Supplementary File A2.[15,35] We assumed that changes in relative risks follow a dose–response relationship,[15,36] and that PAFs combine multiplicatively.[15,37] We calculated changes in mortality and DALYs by applying PAFs to baseline estimates of mortality rates and DALYs in 2012. We quantified the epidemiological uncertainties by calculating uncertainty intervals based on 1,000 iterations of a Monte Carlo analysis that randomly drew the relative risk parameters from their log-normal distributions.

We used publicly available data sources to parameterise the comparative risk analysis. Population and cause-specific mortality data for the year 2012, stratified by age group, were adopted from the ABS and the Global Burden of Disease project, respectively. The diet and weight-related relative risk parameters were adopted from pooled analyses of prospective cohort studies,[16,21] and from meta-analysis of prospective cohort and case-control studies.[38,39,20,17,19,18] The cancer associations have been judged as probable or convincing by the World Cancer Research Fund, and in each case a dose–response relationship was apparent and consistent evidence suggests plausible mechanisms.[38] Table A3 in the Supplementary File provides an overview of the relative risk parameters used.

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Results

Pricing food commodities in relation to their GHG emissions content increases the price of emissions-intensive foods and, as a result of such price changes, decreases demand for those foods. The first three columns of Table 1 list the GHG taxes on food commodities, as well as the associated price and consumption changes, for a price of GHG emissions of $23 /t$CO_2$-eq, the starting price of the Australian carbon tax. In this pricing scenario, the greatest GHG taxes were levied on ruminant meats ($0.91–$1.19/kg), followed by fish ($0.50–$0.65/kg), other meats ($0.27–$0.50/kg), and dairy products ($0.03–$0.15/kg); the GHG taxes on non-animal products, such as fruits and vegetables were below $0.03/kg. The associated price increases were 17% for beef sausages, 6–7% for lamb, beef, and the category of other meat, 3–4% for fish, pork, poultry, bacon and ham, and fats, 1–2% for milk and dairy, and less than 1% for all other food commodities.

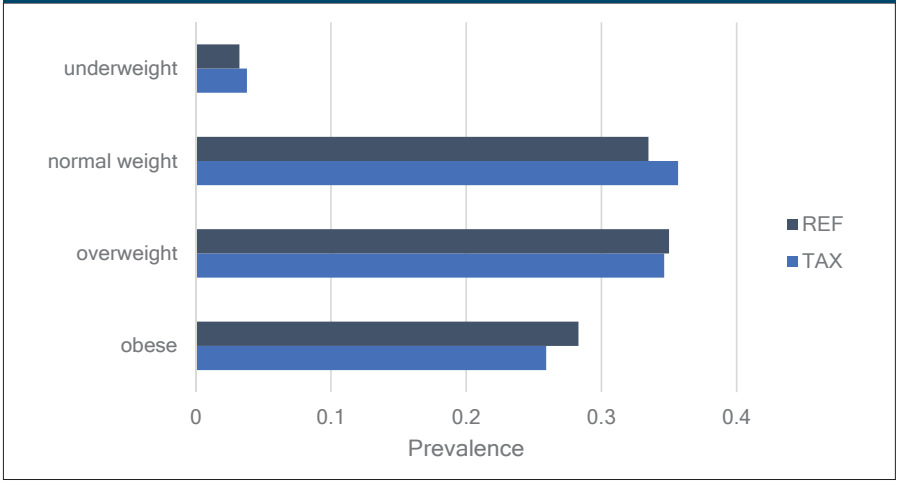
The price changes induced changes in food consumption of similar magnitudes. The consumption of red and processed meat was reduced by 1.8 g per person per day (g/cap/d) and 1.5 g/cap/d, respectively, vegetables consumption was reduced by 1.0 g/cap/d, while fruit consumption was increased by 0.3 g/cap/d. The small increase in fruit consumption is an illustration of substitution effects: when some food commodities become more expensive, consumers shift to those foods that exhibit smaller increases in price and therefore become relatively more affordable. A decomposition of consumption changes by price effects is contained in Table A4 in the Supplementary File. Overall energy intake was reduced by 116 kJ per person per day.

The tax-induced changes in food consumption resulted in changes in dietary and weight-related risk factors, which had implications for levels of obesity and chronic disease mortality and morbidity. The reductions in total energy intake resulted in a shift in the weight distribution of Australians towards lower body weight (Figure 1). The prevalence of underweight increased by 0.6 percentage points, while the prevalence of overweight and obesity decreased by 0.4 and 2.4 percentage points, respectively. About two-thirds (64%) of the changes in weight were due to reduced calories from meat, 13% due to less calories from starches and cereals, 10% from less dairy, 6% from less fish and 6% from reductions in other food commodities (Table 1).

Table 1: Overview of consumption-related parameters. Parameters used in the health analysis are shaded red.

Food commodities	GHG tax	Change in price	Change in consumption			Change in GHG emissions		Revenues
	(AUD/kg)	(%)	(%)	(g/d)	(kJ/d)	(ktCO_2-eq)	(%)	(mill. AUD)
Sausages	1.19	17.25	-11.15	-1.14	-12.02	-475.11	-11.15	87.10
Lamb	1.09	7.35	-7.48	-0.54	-5.18	-204.70	-7.48	58.25
Beef	0.91	6.37	-6.06	-1.13	-9.09	-359.47	-6.06	128.27
White fish	0.65	4.17	-3.28	-0.21	-1.73	-48.72	-3.28	33.08
Other fish	0.60	3.81	-3.78	-0.74	-5.45	-153.83	-3.78	90.16
Other meat	0.50	7.27	-7.90	-5.05	-36.11	-891.99	-7.90	239.31
Pork	0.36	3.05	-1.67	-0.10	-1.12	-12.68	-1.67	17.12
Bacon & Ham	0.27	2.71	-3.16	-0.35	-2.96	-33.44	-3.16	23.55
Poultry	0.21	3.76	-4.00	-1.02	-8.05	-73.83	-4.00	40.75
Cheese	0.15	1.39	-1.33	-0.15	-2.17	-7.98	-1.33	13.63
Cream	0.13	1.75	0.13	0.00	0.03	0.09	0.13	1.74
Fats	0.09	2.97	-2.00	-0.11	-2.89	-3.27	-2.00	3.68
Eggs	0.08	1.07	-0.70	-0.10	-0.66	-2.77	-0.70	9.03
Other dairy	0.04	0.57	-0.96	-0.71	-2.52	-9.25	-0.96	21.95
Fresh veg.	0.03	0.81	-0.87	-0.97	-2.43	-11.65	-0.87	30.53
Tinned & dried fruit	0.03	0.59	-0.29	-0.01	-0.12	-0.09	-0.29	0.73
Milk	0.03	1.85	-1.80	-2.74	-6.57	-24.12	-1.80	30.24
Nuts	0.02	0.15	0.08	0.00	0.11	0.04	0.08	1.09
Other Starches	0.02	0.10	-0.20	-0.01	-0.26	-0.09	-0.20	1.06
Starches	0.01	0.15	-0.48	-1.60	-15.33	-5.41	-0.48	25.71
Sweets	0.01	0.04	-0.14	-0.04	-0.55	-0.08	-0.14	1.27
Fresh fruit	0.01	0.06	0.20	0.29	0.67	0.52	0.20	5.95
Potatoes	0.00	0.16	-0.43	-0.19	-1.17	-0.25	-0.43	1.33
Non-alc. drink	0.00	0.00	0.22	0.21	0.32	0.00	0.00	0.00
Juice	0.00	0.00	-0.08	-1.32	-0.31	0.00	0.00	0.00
Alcohol	0.00	0.00	-0.10	-0.20	-0.42	0.00	0.00	0.00
Total				-17.94	-115.99	-2,318.07	-5.80	865.52

Figure 1: Prevalence of weight states in the reference scenario (REF) and the main tax scenario (TAX).



The changes in the dietary and weight-related risk factors (fruit and vegetable consumption, red and processed meat consumption, and the prevalence of underweight, overweight and obesity) led to 49,500 DALYs averted (95% confidence interval [CI] 43,200-55,200), which corresponded to 1,620 avoided deaths (95%CI 1,430-1,790) of which 400 (95%CI 350-440) were premature deaths that occurred before the age of 70 (Figure 2; Supplementary Tables A5-A6). The majority of DALYs averted were due to reductions in the prevalence of obesity (47,700 avoided DALYs, 95%CI 42,700-52,400; 71% of all positive and negative changes in DALYs), followed by reductions in the consumption of processed meat (8,430 avoided DALYs, 95%CI 5,900-11,010; 13% of all DALY changes), red meat

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(1,660 avoided DALYs , 95%CI 970-2,310; 2% of all DALY changes), and a small increase in fruit consumption (440 avoided DALYs, 95%CI 320-580; 1% of all DALY changes). Diet-related increases in the prevalence of underweight and reductions in vegetable consumption resulted in additional DALYs (for underweight: 6,730 additional DALYs, 5,180-8,280 – 10% of all DALY changes; for vegetable consumption: 1,840 additional DALYs, 1,280-2,600 – 3% of DALY changes), which compensated about 15% of the number of avoided DALYs. About one-third of all avoided DALYs were from avoided cancers, another one-third from the aggregate of other causes, about one-fifth each from CHD and T2DM, and 5% from avoided stroke.

The last two columns of Table 1 list the environmental and public finance impacts of pricing food commodities in relation to their GHG emissions. Price-related changes in food consumption reduced GHG emissions by 2.3 $MtCO_2$-eq, which represents a 6% reduction of food-related GHG emissions (and a reduction of 0.4% with respect to all GHG emissions in Australia, which were 560 $MtCO_2$-eq in 2012). About 90% of the reductions in food-related GHG emissions were due to reduced meat consumption, and about 10% due to reduced consumption of fish. The financial revenues associated with taxing food commodities in relation to their GHG content amounted to $866 million if each tonne of GHG emissions was priced at $23. About 70% of the revenues were collected on meat, 14% on fish, 8% on dairy, 3% on starches and 6% on other foods.

We undertook a sensitivity analysis to explore alternative specifications of our GHG tax scenario. We varied the main scenario, which levied a GHG price of $23/$tCO_2$-eq on all food commodities, along two dimensions. First, we explored a wider set of GHG prices that reflect the price of climate change damages from additional GHG emissions; and second, we constrained the tax to emissions-intensive food commodities, something that could ease the administrative burden of levying a GHG tax on food commodities. For the first analysis, we adopted GHG prices of $12, $37, $57 and $103/$tCO_2$-eq, which reflect the net present value of the climate change damages caused by one additional tonne of GHG emissions using different discount rates (5%, 3%, 2.5%, and the 95th percentile of 3%, which is intended to represent higher than expected economic impacts from climate change further out in the tails of the distribution).[31,32] For the second analysis, we constrained the GHG tax to emissions-intensive food commodities, in particular to animal-based products (meat, fish, dairy, eggs) and fats.

Table 2 lists the results of the two analyses. Changes in the GHG price resulted in proportional changes in key outcomes. Incorporating GHG prices of $12–$103/tCO2-eq into the price of food commodities reduced GHG emissions by 1.2–10.4 $MtCO_2$-eq (3–26%), generated tax revenues of $0.5–3 billion, and resulted in 26,000–198,000 avoided DALYs. Constraining the GHG tax to emissions-intensive food commodities, in particular to animal-based foods and fats, led to smaller changes compared to the main scenario. Consumption changes were 7% less, tax revenues 8% less, and the number of avoided DALYs were 3% less.

Figure 2: Number of avoided disability-adjusted life years (DALYs) by risk factor and disease. Risk factors include changes in the consumption of fruits, vegetables, red meat, processed meat, and changes in the prevalence of underweight, overweight, and obesity. Diseases include coronary heart disease (CHD), stroke, type-2 diabetes mellitus (T2DM), several site-specific cancers, and an aggregate of other diseases/causes of death.

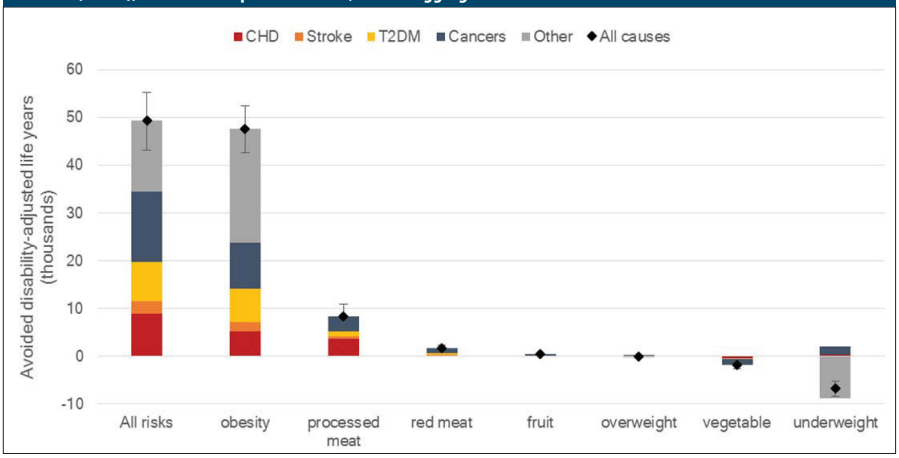

Table 2: Sensitivity analysis with respect to the coverage of food-related emissions pricing, and the magnitude of GHG emissions. In the TAXadj scenario, emissions taxes are levied only on emissions-intensive foods (animal-based foods and fats) compared being levied on all foods in the main scenario (TAX). In the SCC scenarios, emissions prices are aligned with social-cost-of-carbon (SCC) estimates under different discount rates (5%, 3%, 2.5%, and the 95th percentile of 3%).

Selected parameters	TAX	TAXadj	SCC (5%)	SCC (3%)	SCC (2.5%)	SCC (95th of 3%)
GHG price (AUD/tCO2-eq)	23	23	12	37	57	103
Coverage	all foods	animal-based	all foods	all foods	all foods	all foods
Consumption change (kcal/d)	-27.72	-25.77	-14.46	-44.60	-68.71	-124.15
Change in GHG emissions ($MtCO_2$-eq)	-2.32	-2.30	-1.21	-3.73	-5.74	-10.38
Change in GHG emissions (%)	-5.80	-5.76	-3.03	-9.33	-14.38	-25.99
Tax revenues (AUD million)	866	798	465	1,340	1,950	3,046
DALYs avoided (thousands)	49.45	48.10	26.11	78.29	117.59	198.25

Discussion

Our results suggest that incorporating the price of food-related GHG emissions into the price of food commodities in Australia could be beneficial for population health, while generating public finance revenues and supporting Australia's emission reduction commitment. We found that extending the price of GHG emissions that prevailed under the Australian Carbon Pricing Mechanism to food commodities could lead to 49,500 avoided DALYs, primarily due to reductions in energy intake and associated reductions in obesity levels; reduce food-related GHG emissions by 2.3 $MtCO_2$-eq, primarily due to reductions in the consumption of animal-based food commodities; and generate public revenues of $865 million, most of it from emissions taxes on meat.

The estimated impacts represent a reduction in DALYs of 1%, a reduction in food-related GHG emissions by 6% (a reduction of total GHG emissions in Australia by 0.4%), and an increase in the tax revenues from taxes on provision of goods and services of 1% (and a 0.2% increase in total tax revenues). Comparing the health results of our main scenario to other literature estimates suggests that the number of avoided DALYs from integrating the price of GHG emissions into

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the price of food commodities exceeds the estimated number of avoided DALYs from diet and exercise interventions in Australia by one order of magnitude,[40] and it is comparable to the estimated effects of traffic-light nutrition labelling.[26] If estimates of the social cost of GHG emissions were used instead of the former Australian carbon price, the impacts of food-related GHG pricing could increase by up to a factor of four in each dimension of avoided DALYs, emissions reductions and public revenues.

Our results suggest that incorporating food-related GHG emissions into future emissions pricing mechanisms in Australia would be a no-regret policy from health, environmental and public finance perspectives. However, several policy design aspects must be considered. Firstly, one problem with policies that would result in higher food prices is the impact that those could have on low-income households. Such concerns featured prominently in the discussion of the Australian Carbon Pricing Mechanism, and it resulted in a comprehensive set of support measures for low-income households. Extending the GHG price to food commodities would generate additional revenues that could be used to increase those support measures. Under the Australian Carbon Pricing Mechanism, households would have received financial assistance valued at $14.3 billion over four years.[41] The financial revenues from extending the GHG price to food-related emissions would increase assistance measures by about 24% if all revenues were used for that purpose each year.

Secondly, one reason that food and agriculture was so far spared from carbon pricing initiatives has been the difficulty of accurately measuring agriculture-related emissions. As a result, the administrative costs of levying emissions taxes on agriculture could be high. One response that would reduce the measurement burden would be to constrain the pricing of food-related GHG emissions to the most emissions-intensive food commodities. Our sensitivity analysis indicated that limiting food-related emissions pricing to animal-based foods and fats would result in similar impacts on health, emissions and public finances to an emissions pricing scheme with full coverage. Another way of reducing the administrative costs is to implement emissions taxes on outputs (as consumption taxes) instead of on inputs. Using emissions-related output taxes on food commodities acknowledges that options for reducing emissions apart from output reduction are limited, and it addresses the problems of carbon leakage related to the high substitutability of food commodities, and of the high monitoring costs of agricultural emissions.[42,43] Collecting emissions-related output taxes would be possible with existing ways of collecting other consumption taxes, such as value-added tax (VAT).

Thirdly, we did not analyse the impacts that food-related GHG pricing could have on the economy or employment. However, we can compare our results with economic assessments of the Australian Carbon Pricing Mechanisms, which constituted a much more comprehensive carbon pricing policy than the food-related part we analysed here. A detailed analysis of the Australian Carbon Pricing Mechanism estimated that a comprehensive carbon pricing policy could decrease economic growth by about 0.1% per year (about $1.3 billion), but would not significantly affect the level of employment.[7] The health impacts we assessed in this study can be estimated by using the value of statistical life (VSL) or life year (VSLY), the latter of which gives greater weight to lives lost or saved early.[44] Using a recommended VSL of $4.2 million and a VSLY of $182,000,[45] adjusted to 2012 prices, yields values of health benefits of $5.3–6.5 billion. Thus, the value of life benefits associated with extending carbon pricing to food-related GHG emissions could far outweigh the total economic costs of the Australian Carbon Pricing Mechanism.

While this is the first analysis of its kind for Australia, other country case studies have estimated the health impacts of incorporating the price of GHG emissions into the price of food commodities in the UK and New Zealand.[12,13] For example, Briggs and colleagues[12] estimated that about 7,770 deaths could be averted, 19 $MtCO_2$-eq of food-related emissions could be reduced, and about GBP 2 billion in public revenues could be generated if the social cost of carbon was integrated into the price of food commodities in the UK. Our results are smaller than the UK estimates in absolute (1,620 averted deaths, 2.3 $MtCO_2$-eq reduced, $866 million in tax revenues), but (except for the emissions estimates) they become roughly comparable when taking into account the difference in population between the UK and Australia (64 million in the UK, 23 million in Australia), higher tax levels in the UK study, in particular for beef (1.76 GBP/kg versus 0.91 AUD /kg), and the inclusion of GHG emissions related to land-use change, which accounted for three-quarters of emissions reductions in the UK study.

There are several limitations to this analysis that should be considered when interpreting the result. Firstly, the consumption data used could have led to an underestimate of consumption changes. As stated by the ABS, food consumption data was gathered using a 24-hour dietary recall on all foods and beverages consumed on the day prior to the interview and, where possible, at least eight days after the first interview, and respondents were contacted to participate in a second 24-hour dietary recall via telephone interview. The risk of under-reporting has been emphasised repeatedly by the ABS. If the baseline consumption estimates used in this represented an underestimate, then the effects derived from those would also be underestimated. Thus, the actual impact of food-related GHG pricing could be larger than estimated in this study.

Secondly, the classification of food commodities did not allow for all food commodities to be included in our health modelling. In particular, we found large price-related changes in the consumption of 'other meat', which includes mixed dishes with variable portions of different types of meat. It was not possible for us to further disaggregate this category and attribute its changes to changes in specific risk factors, such as changes in red meat and changes in processed meat. Excluding the reduction in the consumption of other meat dishes in our health modelling has likely resulted in an underestimate of consumption-related health benefits due to the beneficial effects that reductions in red and processed meat consumption have on non-communicable disease incidence and mortality.[17,20,38,46,47]

Thirdly, our estimate of food-related emissions reductions excludes factors that could change the estimated emissions reduction. Some factors could have led to greater emissions reductions had they been included. For example, we did not account for emissions from land-use change and post-farm-gate activities, such as processing, packaging, and transportation to households, and the international estimates of food-related emissions intensities we adopted could have lowered the average estimates for the emissions-intensive food production in Australia. We would have preferred using

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national estimates of food-related GHG emissions in Australia, but systematic meta-analyses of national studies do not exist, and individual studies are too heterogeneous in their methodologies to be compared in a meaningful way.[48] A factor that could reduce future changes in food-related emissions is technological change, something the static emissions intensities used in our study could not resolve. However, the mitigation potential of agricultural commodities, particularly livestock products, is limited by the characteristics of the product, such as methane emissions from ruminants. While malleable to some degree, this cannot be changed completely.[49,50]

Finally, we used a comprehensive and economically consistent set of food demand elasticities, but we had to rely on UK data for this level of detail and methodological consistency. We would have preferred to use national estimates of food demand elasticities instead of adapting those from the UK. However, the only available estimate was based on a limited data set, the commodity coverage was small, and some of the results ran counter to economic intuition,[24] and a second set of Australia-based elasticities were adjusted for Australia from an econometric study of the UK whose statistical methods are considered outdated.[23,25]

Conclusion

Australia is committed to an ambitious emissions reduction target that is unlikely to be achieved without consistent emissions pricing.[2-5] Our analysis suggests that including food-related GHG emissions in such pricing mechanisms would confer benefits to population health, contribute to reducing food-related GHG emissions, and generate additional revenues for public finance. Such considerations should be taken into account in future reviews of, and potential adjustment to, Australia's climate policy.

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Supporting Information

Additional supporting information may be found in the online version of this article:

Supplementary File A1: Supplementary economic methods.

Supplementary File A2: Supplementary health methods.

Supplementary Table A1: SOwn-price, cross-price, and expenditure elasticities used in this study (adopted from Tiffin et al., 2011).

Supplementary Table A2: Food commodities, price and emissions data.

Supplementary Table A3: Relative risk estimates associated with changes in risk factors (mean estimate and 95% confidence intervals).

Supplementary Table A4: Decomposition of consumption changes by price changes. Own-price elasticities determine consumption changes due to price changes of the same commodity, cross-price elasticities determine consumption changes due to price changes of other commodities, and expenditure elasticities determine consumption changes due to changes in food expenditure.

Supplementary Table A5: Changes in mortality due to changes in risk factors.

Supplementary Table A6: Changes in disability-adjusted life years (DALYs) and years of life saved (YLS) due to changes in risk factors.

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