Global Greenhouse Gas Taxes on Food Products: Economy-wide, Environmental and Dietary Implications

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Preliminary draft. Please do not cite.

Summary

Agricultural and food systems are contributing over 25% of global GHG emissions. Demographic changes and increasing income are expected to further push the global diet towards more meat-oriented and emission-intensive food items, as a result, agricultural GHG emissions could significantly increase in the long-run, which would make it almost impossible to keep the global temperature increase *well below 2°C*, as desired by the Paris Climate Agreement. Therefore, reducing food-related GHGs is a crucial step in meeting the stringent climate change targets.

The focus of this paper is to provide a global assessment of food-related GHG emissions taxation. For this purpose, we use a multi-sector multi-region CGE framework, based on the GTAP model. We further improve and complement the GTAP framework in several ways. First, we develop the GTAP database (2011 reference year) with updated agricultural production targeting for 133 regions. Second, we develop a GTAP-consistent food balance sheets with dietary and nutritional information covering all 141 regions in the database. Finally, we complement the modelling framework by including the non-CO_2 GHG emissions and air pollution accounts.

We explore scenario with the carbon tax rate of \$35/ton CO_2-eq. (\$2010 PPP) and use the sensitivity analysis, varying tax between \$15/ton CO_2-eq. and \$55/ton CO_2-eq. In the central case, global non-CO_2 GHG emissions decrease by 0.85% (0.4%-1.3% under varying tax rates), while global GHG emissions fall by around 0.3%. Reductions highly vary by regions, with the highest cuts observed in African and South American countries (reaching up to 4%-5%). There are no significant co-benefits for air pollution changes. NH_3 emissions show the largest change (-0.7%), while emissions of other air pollutants decline by less than 0.1%.

With increasing food prices, households adjust by reducing volumes of food consumption and shifting from more to less carbon intensive commodities. Countries with initially lower per capital calorific consumption experience higher relative reductions in food supply, facing the risk of trespassing the lower bound of WHO-recommended minimum per capita food requirements.

There is no significant impact on global welfare, as it declines by around 0.002% (-\$1.4 billion). At the regional level, Sub-Saharan Africa countries experience the largest reductions, exceeding 0.4% in the cases of Uganda and Tanzania. In terms of welfare cost of GHG emission reductions, a global average equals 13.4 \$/ton CO_2-eq. North African, Middle Eastern and EU countries show negative welfare cost of GHG emission cuts, while in the number of countries these costs could exceed \$100/ton CO_2-eq.

Keywords: *Computable general equilibrium modelling, Global Trade Analysis Project, Emission taxes, Food products, Welfare, Dietary impacts.*

1. Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), agriculture, forestry and other land use activities contribute approximately a quarter of the global greenhouse gas (GHG) emissions. Demographic changes and increasing income are expected to further push the global diet towards more meat-oriented and emission-intensive food items, as a result, agricultural GHG emissions could significantly increase in the long-run. Even with no shifts in the global diet, according to Hedenus et al. (2014), food-related emissions could grow from 7.1 Gton CO_2-equivalent per year in 2000 to 13 Gton CO_2-eq./year in 2070, which would make it almost impossible to keep the global temperature increase *well below 2^oC*, as desired by the Paris Climate Agreement. Therefore, reducing the food-related GHG emissions is a crucial component in meeting the stringent climate change targets. Yet, in many studies, agricultural and food sectors have been excluded from the global climate policy assessment because of the difficulties in monitoring related emissions, shortage in both policy instruments and technological solutions towards food-related climate mitigation, as well as potential regressive impacts on welfare and food security, especially in the developing countries (Springmann et al., 2016).

To fill this gap, a number of recent studies have explored environmental and health implications of strategies to reduce GHG emissions in food and agricultural sectors (Friel et al., 2009; Hedenus et al., 2014; Tilman and Clark, 2014; Springmann et al., 2016). While providing a detailed analysis of impacts on health, emissions profiles and dietary changes, most of the studies are missing economy-wide effects of the policies under consideration, as well possible inter-sectoral linkages.

The focus of this paper is to provide an assessment of food-related GHG emissions taxation using a multi-sector multi-region computable general equilibrium (CGE) framework – the Global Trade Analysis Project (GTAP) model. To reach our goal, we further improve and complement the GTAP framework in several ways. First, we develop the GTAP database (2011 reference year) with updated agricultural production targeting (APT) for 133 regions, following the approach outlined in Chepeliev and Aguiar (2018).

Second, we develop a GTAP-consistent food balance sheets with dietary and nutritional information covering all 141 regions in the database. This allows us to track changes in the per capita food supply quantity, as well as protein and fat supply levels by country.

Finally, we complement the GTAP-E modelling framework by including the non-CO_2 GHG emissions and air pollution accounts, in addition to the CO_2 emissions already embedded into the model. We source the non-CO_2 GHG emissions data from Irfanoglu and van der Mensbgrugghe (2015), which provides data for three major non-CO_2 gases (CH_4, N_2O and the group of Fluorinated gases).

The air pollution database comes from Chepeliev (2018). This database distinguishes 10 different types of air pollutants. Changes in the non-CO_2 GHG emissions and air pollution are tracked in a post-simulation modelling routine.

Based on the volumes of GHG emissions associated with food production and estimates of the Social Cost of Carbon (SCC), which represents the average global damage from 1 ton of CO_2-eq. emissions, we estimate emissions tax rates. Following IMF (2015), we use a central value of \$35/ton CO_2-eq. (\$2010 PPP), along with a lower bound of \$15/ton CO_2 and an upper bound of \$55/ton CO_2. The lower and upper bounds are based on the SCC meta-analysis by van den Bergh and Botzen (2014). We implement the range of CO_2 taxation scenarios using the Systematic Sensitivity Analysis (SSA) approach developed by Arndt and Pearson (1998). With this approach, we accompany central scenario (\$35/ton CO_2-eq. tax rate) with 95% confidence intervals and indicate them using error bars.

In terms of methodology, our paper contributes to the existing literature on the disaggregation of agricultural sector and representation of food balances in the CGE modelling. From the policy side, our analysis extends the existing literature on the quantitative assessment of the food-related GHG emissions pricing. We provide new insights into economy-wide, environmental and dietary implications of such policies, with a particular focus on the cost-benefit (welfare) analysis at the country level – a link that most studies have been missing so far. In addition, as global GHG taxes on food products also change agricultural trade patterns, our paper provides assessment of such impacts, looking into the most affected countries and regions.

2. Methods

For the purpose of this study, the GTAP modelling framework is extended and complemented in several ways. These extensions include FAO-based agricultural production targeting, incorporation of food balance sheets with dietary and nutritional information, as well as addition of non-CO_2 GHG emissions and air pollution accounts. Below we discuss these extensions in more details.

2.1. Agricultural production targeting

The first step of our GTAP data framework extension includes improvements of the agricultural output targeting by sectors based on the FAO data. First, this allows us to overcome some limitations of the currently used APT approach. Second, in this way we are able to harmonize GTAP database with the FAO data, which further helps to link food balance sheets and non-CO_2 GHG emissions to GTAP.

Detailed representation of the agricultural sector is one of the key GTAP features. GTAP 9 Data Base (Aguiar et al., 2016) distinguishes 12 agricultural sectors, in addition to eight food sectors. To reach such level of details, first agricultural input-output (IO) table is used to split sectors, where necessary (Peterson, 2016). Second, APT for 12 agricultural sectors is applied to selected countries (Zekarias et al., 2016), using OECD (OECD, 2017) and EU (Boulanger et al., 2016) data.

While current approach substantially improves representation of the agricultural and food sectors in the GTAP database, it has several limitations. First, OECD-derived data include high share of unclassified commodities (over 10%-20% of total agricultural output in many countries). As these commodities are not mapped to the specific commodity group, additional assumptions have to be made for re-distribution of this category. Second, while current APT approach covers 46 countries, which represents 70% of the global agricultural output, most developing countries (e.g. India) are not targeted. Finally, some agricultural commodities are not reported by OECD and processed food output is used for targeting (e.g. sugar output is used to derive targets for sugar cane).

To overcome these limitations, as well as to add consistency between GTAP and FAO data, we use FAOSTAT (FAO, 2018) values of agricultural production for the updated APT approach. This allows us to target output at the disaggregated commodity level and avoid potential issues with the re-distribution of unclassified commodities. Using this approach we estimate APTs for 133 GTAP regions (out of 141 total regions), as well as get output quantity and price estimates at the disaggregated commodity level for each region. Figure 1 provides an overview of steps used to estimate agricultural production targets. A more detailed discussion of this approach is provided in Chepeliev and Aguiar (2018).

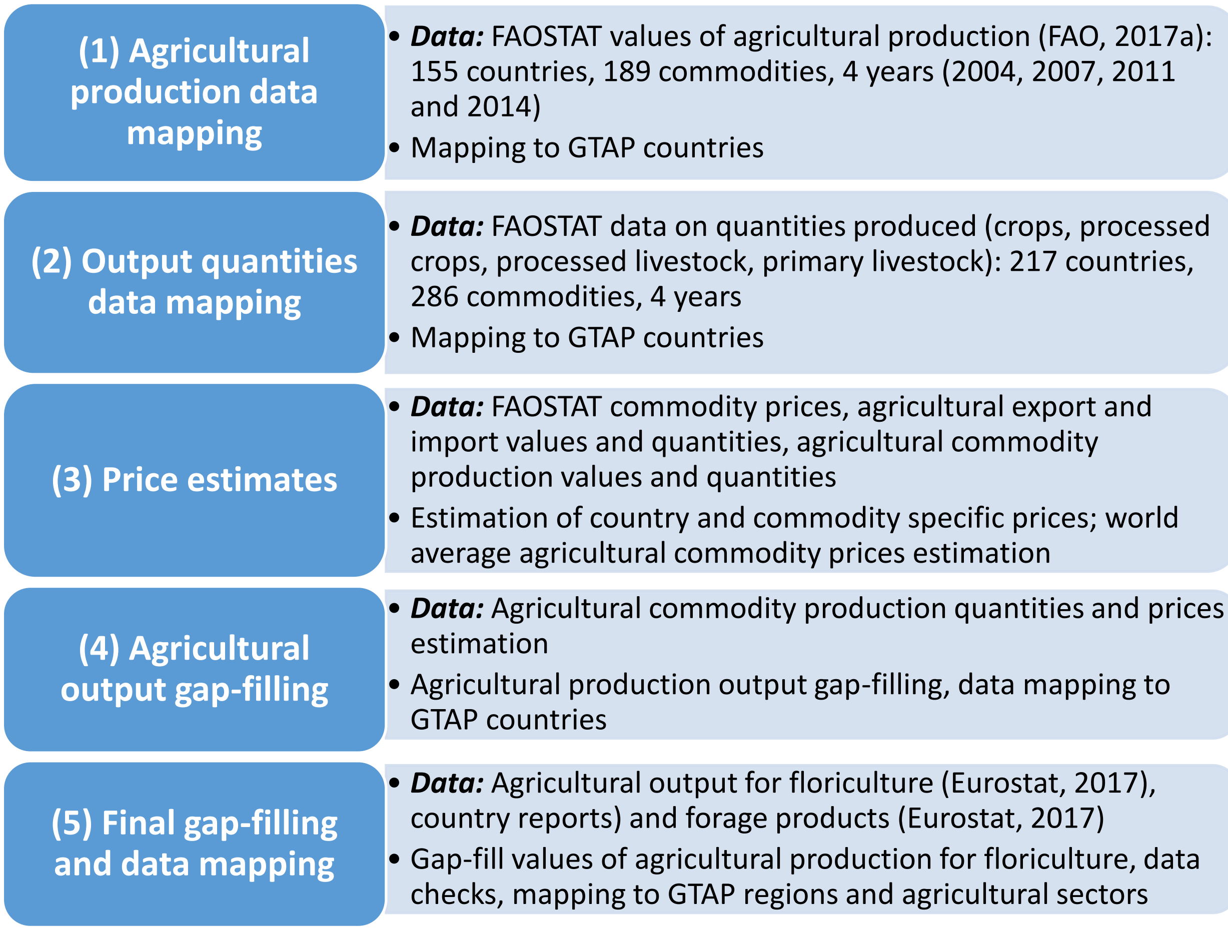

Figure 1. Steps to estimate agricultural production targets from FAO data for GTAP Data Base

Source: Authors.

With updated agricultural production targets, we construct the GTAP 9.2 database with 2011 reference year. This database covers 141 regions and 57 commodities (Aguiar et al., 2016). On average, produced GTAP database reports similar agricultural output for the developed regions (most of them undergo APT within the GTAP build) and larger value of agricultural production for many developing countries (Figure 2). However, in the case of most Middle Eastern countries newly developed database reports lower values of agricultural output. Interpretation of these results should also take into account that apart from APT, there are numerous other adjustments going on within the GTAP build process and final database output might deviate from sector and country-specific APT targets.

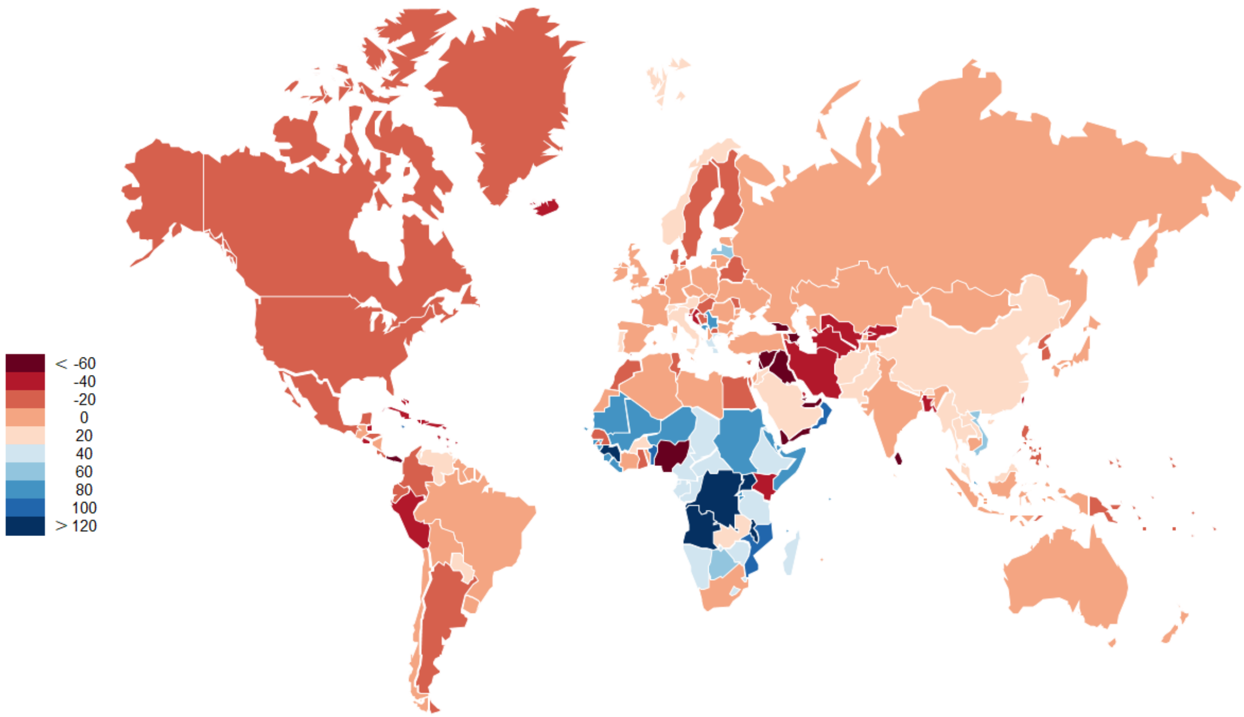

Figure 2. Difference between aggregate agricultural output in the GTAP 9.2 database with FAO-based agricultural targets and standard GTAP 9.2, %

Source: Developed by authors.

Note: Aggregate agricultural output corresponds to the output of GTAP sectors 1-12 (see Aguiar et al. (2016) for sectoral listing). Percentage difference are estimated relative to the standard GTAP 9.2 agricultural output. Positive percentage differences indicate that database with FAO-based agricultural targets reports larger values of production than the standard database.

2.2. Dietary and nutritional database

To be able to track the dietary and nutritional outcomes of the emission pricing of food commodities, we develop a dietary and nutritional database using FAO Food Balance Sheets (FBS) data (FAO, 2018), which we further link to GTAP. The main idea is to link food supply, protein supply and fat supply (capita/day) to the final consumption categories of the GTAP database. This requires mapping between FBS categories and GTAP sectors.

FBS data are organized by categories based on the supply-utilization accounts. FBS categories include both raw and processed commodities. In some cases, FBS category consists of a single commodity (e.g. banana, cassava, etc.), which could be directly mapped to the GTAP sectors, while in other cases, a mix of raw and processed commodities is reported. For instance, FBS "Wheat and products" category includes wheat, flour wheat, bread and pastry. In most cases, FAO does not report production or consumption quantities of the corresponding processed commodity (e.g. wheat, bread), therefore some additional assumptions should be made to disaggregate FBS categories between GTAP sectors, as required. To address this issue, we developed a mapping between GTAP sectors and FBS categories (Appendix A).

Out of 98 FBS categories, 55 are mapped 1-to-1 to GTAP sectors. In case of other 42 FBS categories, we distribute dietary and nutritional data between multiple sectors based on values shares. Each of the FBS category with 1-to-n mapping we define primary sector, which in most cases represents raw (unprocessed) commodity (Appendix A, column 4).

In case of the FBS “Wheat and products” category, Wheat (“wht”) is a primary sector, while Food product nec “ofd” is non-primary sector. To estimate shares for the FBS categories re-distribution, we use GTAP final consumption expenditures for primary sectors and value of intermediate consumption of primary commodity by non-primary sector(s). In the example above, we first added together households’ final consumption expenditure on “wht” and value of “wht” use by “ofd”. We then estimated value share of “wht” consumed by households and “wht” used by “ofd” in this sum. Corresponding shares were used to distributed FBS “Wheat and products” category between “wht” and “ofd” GTAP sectors. In case of two FBS categories – “Offals, edible” and “Milk – excluding butter”, only final consumption values were used to derive re-distribution shares.

Within the current mapping, we allocate all FBS categories to the GTAP food and agricultural sectors only, thus ignoring households’ food consumption in hotels and restaurants. Within the GTAP 9.2 sectoral classification accommodation and food services are aggregated with the trade activities, which complicates food and nutritional data mapping. In the upcoming GTAP 10 database, accommodation and food services would be disaggregated from the trade activities, thus providing a better opportunities for representing food consumption in hotels and restaurants.

Figure 3 represents global per capita distribution of food, protein and fat supply by GTAP food and agricultural sectors. In terms of food supply, global average per capita calorific consumption equals 2860 kcal/capita/day and 3 GTAP sectors, namely Food products nec, Processed rice and Vegetable oils account for almost 50% of this number. In case of fat supply, global average equals 82 g/capita/day, while vegetable oils, other meat and dairy constitute 72% of the fat consumption. Finally, protein supply with a global average of 80 g/capita/day is more equally distributed between GTAP sectors (than food and fat supply). Nine GTAP sectors have over 5% shares in the global per capita protein supply, with Food products nec being the largest contributor – 22.9% (Figure 3).

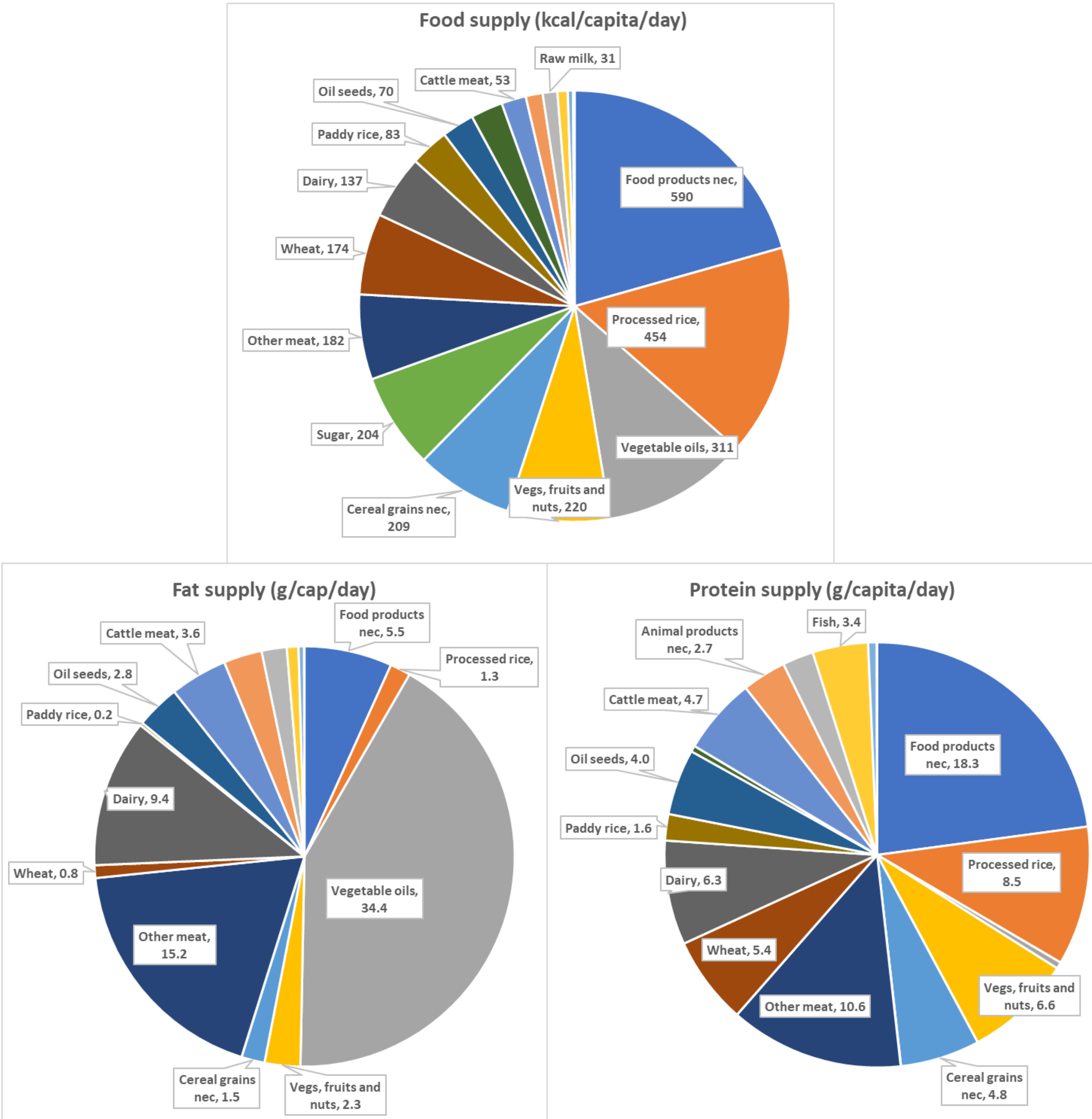

Figure 3. Global weighted average per capita distribution of food, fat and protein supply by GTAP food and agricultural sectors

Source: Authors' estimates based on Aguiar et al. (2016), Chepeliev and Aguiar (2018) and FAO (2018).

Sectoral distributions of food, fat and protein supply have a high variation by countries and regions. In many cases, standard deviation exceeds mean estimate over regions. For instance, in case of Malawi over 66% of total food supply is associated with Cereal grains nec sector, while for 97 out of 141 regions this share is less than

10%. Appendix B reports mean (world average) and standard for per capita food, fat and protein supply by GTAP sectors.

2.3. Non-CO_2 GHG emissions and air pollutants

Standard GTAP database includes only CO_2 emissions from fuel combustion (Aguiar et al., 2016). While agricultural and food sectors generate some of these emissions, they constitute a small part of aggregate GHG emissions in these sectors. To account for other non-CO_2 GHG emissions, we rely on data compiled by Irfanoglu and van der Mensbrugghe (2015). This database reports emissions for three non-CO_2 GHGs – N_2O, CH_4 and F-gases. We also complement the modelling framework with air pollution accounts. This would allow us to estimate potential air pollution co-benefits from emissions taxation in food and agricultural sector. The air pollution database comes from Chepeliev (2018). This database distinguishes 10 different types of air pollutants.

For 4 out of 10 air pollutants agricultural and food sectors contribute over 20% of global emissions, while in case of NH_3 this share reaches almost 90% (Figure 4). Therefore, we might expect some substantial air pollution reduction co-benefits from GHG taxation in food and agricultural sectors.

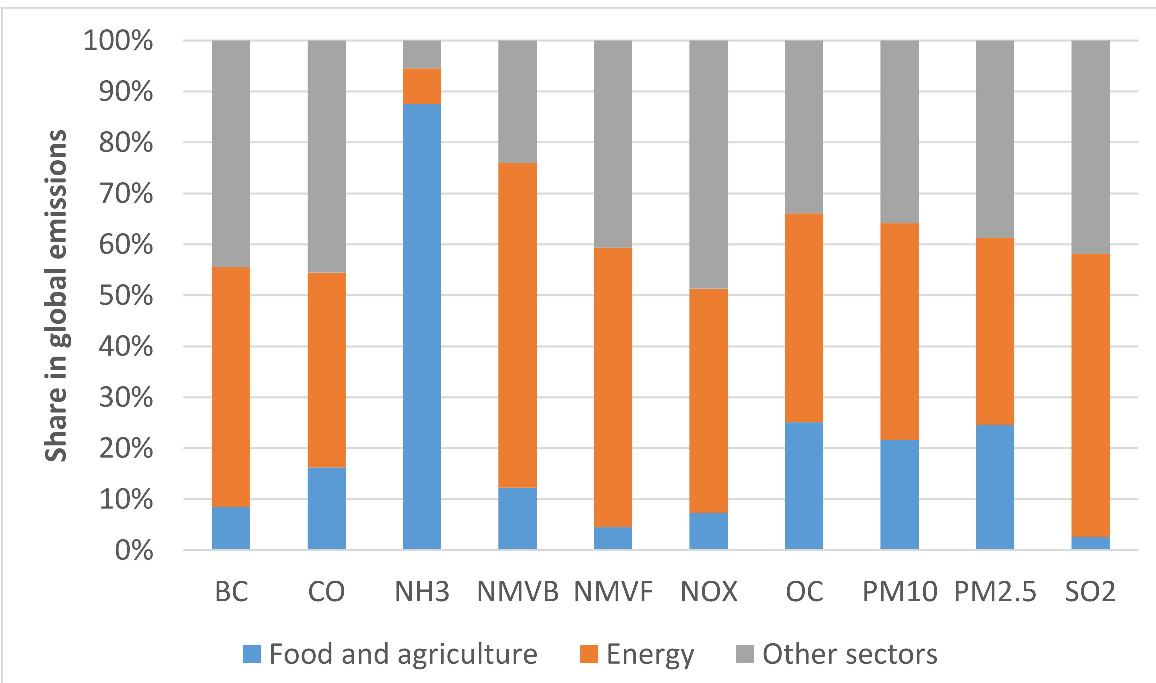

Figure 4. Global emission shares by aggregate sectors and air pollutants

Source: Based on Chepeliev (2018).

Note: Food and agricultural sectors correspond to GTAP sectors No. 1-12, 14 and 19-26; Energy includes GTAP sectors 15-17, 32, 43 and 44; Other sectors include those not classified under the first two groups. See Aguiar et al. (2016) for GTAP sectoral classification.

In case of both datasets, emissions are linked to economic activities and three sets of emission drivers: consumption (by intermediate and final users), endowment use (land and capital) and output. Non-CO_2 GHG emissions dataset relies on EDGAR 4.2 (JRC/PBL) and FAOSTAT emissions dataset (FAO, 2018). Ari pollutions database uses data from EDGAR 4.3.1 (JRC, 2016) and some supplemental data from IIASA (IIASA, 2017).

Out of 5.5 Gigatons (Gt) of non-CO_2 GHG emissions in agricultural and food sectors in 2011, almost half are associated with Cattle sector ("ctl"), while other 23% come from Paddy rice ("pdf") and Raw milk ("rmk") sectors (Figure 5). All these sectors represent raw commodities and in most cases have relatively small share of households' final consumption. To track GHG emissions at the final consumption level, we estimate GHG emissions (both CO_2 and non-CO_2) embodied in the final households' consumption by GTAP sectors and regions. To estimate such flows, we follow Peters (2008), who estimates CO_2 emissions embodied in bilateral trade, and modify corresponding approach for our needs.

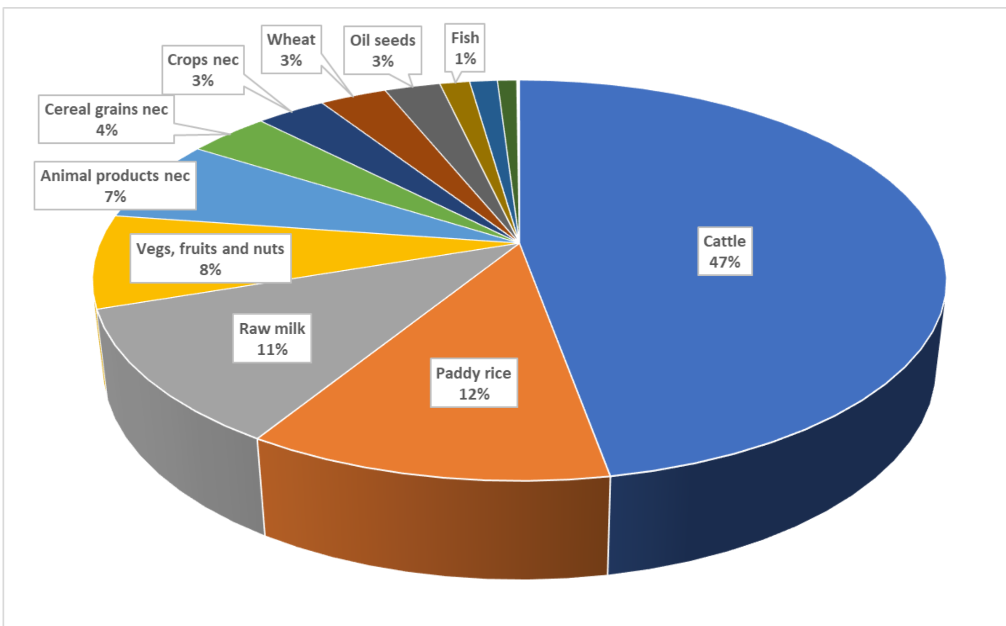

Figure 5. Distribution of global non-CO_2 GHG emissions by GTAP agricultural and food sectors in 2011

Source: Based on Irfanoglu and van der Mensbrugghe (2015).

Country-specific GHG emissions per unit of output by industries are used to estimate emissions associated with final consumption flows. This method assumes that the production technology is based on fixed proportions (i.e. in a given sector and country, the same production technology is used to produce domestic and exported commodities) (Peters, 2008). This allows us to decompose emissions from domestic output into its sales disposition, i.e., exports or domestic sales. For every commodity, the total GHG emissions embodied in final households' consumption of region r (f_r) are estimated as

$$f_r = F_r(I - A_r)^{-1}e_r \qquad (1)$$

where F_r is a vector of country-specific GHG emissions per unit of output by industries, I is the identity matrix, A_r is the technological matrix, which represents the industry requirements of domestically produced products in region r and e_r corresponds to the final households' consumption value in region r.

According to our estimation, Cattle meat ("cmt") and Food product nec ("ofd") are by far the largest sectors with consumption-embodied food and agriculture GHG emissions (Figure 6). Out of 5.5 Gt of GHG emissions (embodied into final consumption of food products), these two sectors correspond to 31.2% of global emissions. At the same time, raw commodity sectors, such as Cattle, Paddy rice and Raw milk have much lower shares in terms of GHG emissions embodied into households' final consumption (compared with the sectoral level data). In this assessment, both combustion-related CO_2 emissions and non-CO_2 GHG emissions are included into the GHG emissions embodied into final households' consumption.

At the regional level, China has the largest food-related GHG emissions (15.3% of the global share), followed up by India (13.9%) and USA (8.3%). Changes in the non-CO_2 GHG emissions and air pollution are tracked in a post-simulation modelling routine. Changes in emissions are linked to emission drivers specified in the corresponding databases (Irfanoglu and van der Mensbrugghe, 2015; Chepeliev, 2018).

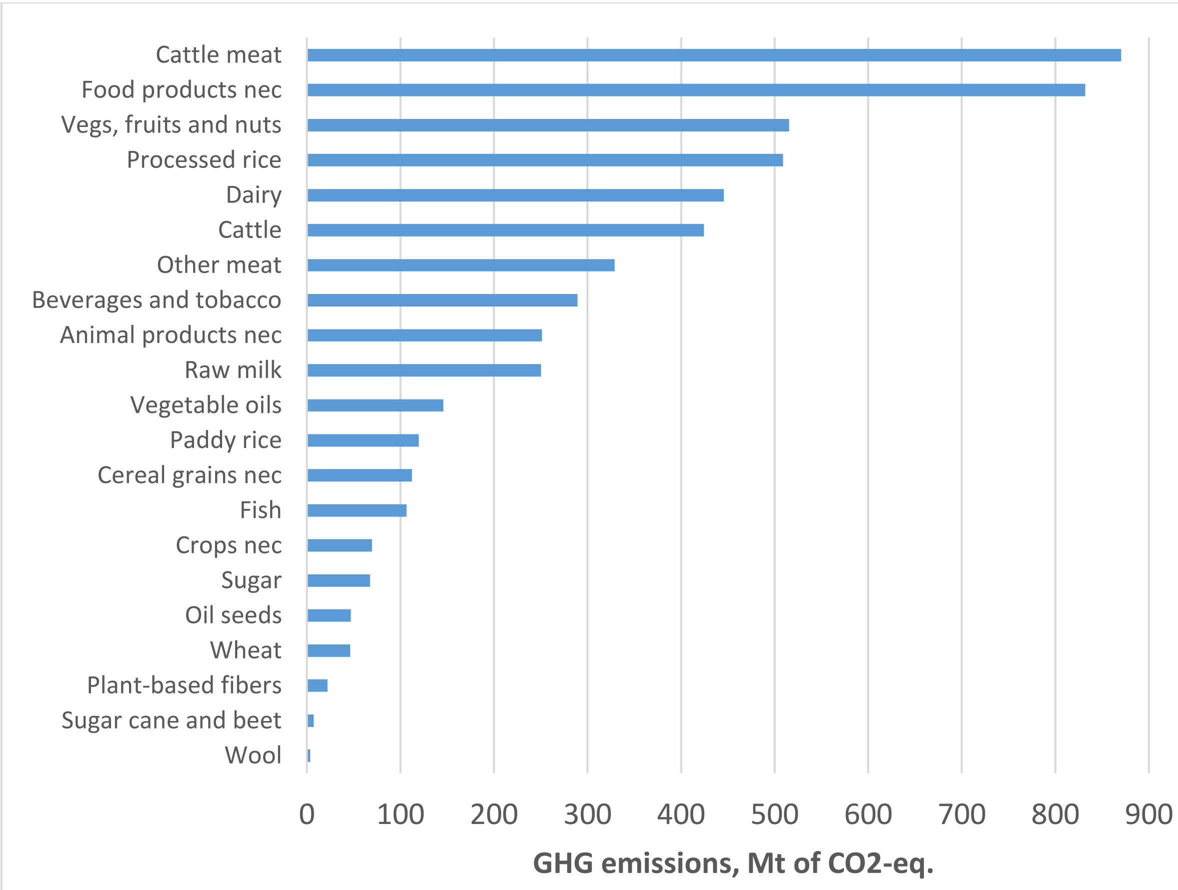

Figure 6. Global GHG emissions embodied into final households' consumption by GTAP agricultural and food sectors, 2011[1]

Source: Authors' estimates based on Irfanoglu and van der Mensbrugghe (2015) and Aguiar et al. (2016).

3. Policy scenarios

For the purpose of policy simulations, we aggregate 57 GTAP sectors into 35 aggregate sectors (Appendix C) and map 141 GTAP regions to 64 aggregate regions (Appendix D). Table E.1 (Appendix E) represents distribution of GHG emissions embodies into final households' consumption of food products by aggregated regions.

Based on the volumes of GHG emissions embodied into final households' consumption of food items (see Section 2.3 for more details) and estimates of the Social Cost of Carbon (SCC), which represents the average global damage from 1 ton of CO_2-eq. emissions, we estimate emissions tax rates. Based on the IMF (2015),

[1] "Mt" stands for million tons.

we use a central value of $35/ton CO_2-eq. ($2010 PPP), along with a lower bound of $15/ton CO_2-eq. and an upper bound of $55/ton CO_2-eq. The lower and upper bounds are based on the SCC meta-analysis by van den Bergh and Botzen (2014). We multiply GHG emission volumes (embodied into households' food consumption) by the SCC estimates and derive equivalent final consumption tax rates for each food commodity and aggregate region. Estimated tax rates highly vary by commodities and regions. Figure E.1 indicates global average final consumption tax rates corresponding to the introduced food carbon charges. Cattle meat sector faces by far the highest additional tax rate (36.3% in the central case scenario), followed by Paddy rice (13.7%), Cattle meat (8.3%), Raw milk (8%) and Processed rice (7.8%). All other sectors experience tax rate increase of 6% and below (Figure F.1).

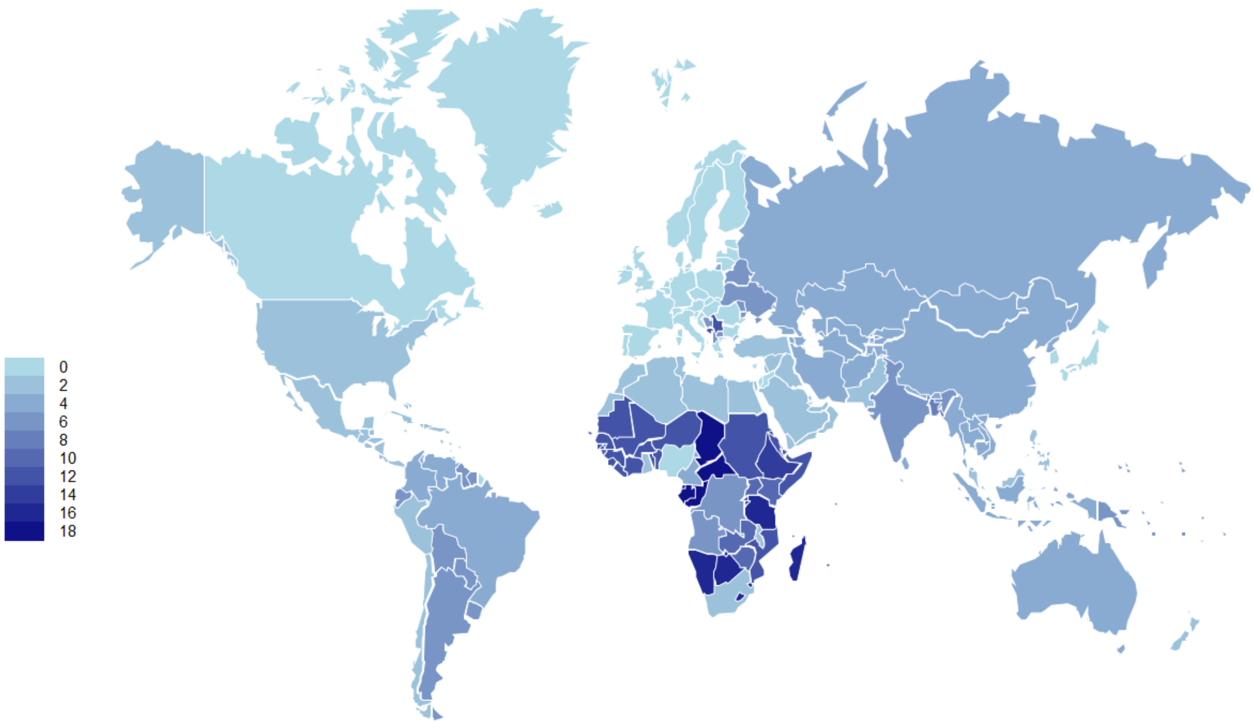

Figure 7. Region-average tax rates imposed on final households' consumption of food commodities, % of final households' food consumption value

Source: Authors' estimates based on Irfanoglu and van der Mensbrugghe (2015) and Aguiar et al. (2016).

While in general sector-average (GHG emissions-related) food consumption tax rates are around 5%, in case of some African countries and regions, they could reach up to 16%-19% (e.g. Ethiopia, Tanzania, Madagascar, Central Africa) (Figure 7). General pattern is that estimated GHG tax rates on food products are higher (than world average) in the developing countries and lower in the developed countries, due to the differences in food prices and higher per capita food consumption in advanced economies. As developing countries tend to have lower food prices and consume less food per capita than advanced economies, single world average GHG tax rate results in a higher share of tax revenue in the households' food consumption value. Composition of food consumption towards higher priced commodities in the developed countries also matters here.

These factors towards higher level of households' final expenditures on food in advanced economies are only partially offset by lower food-related emissions per capita in developing countries (Figure 8). In general, there is no significant trend towards correlation between increasing GDP and per capita food-related GHG emissions by countries.

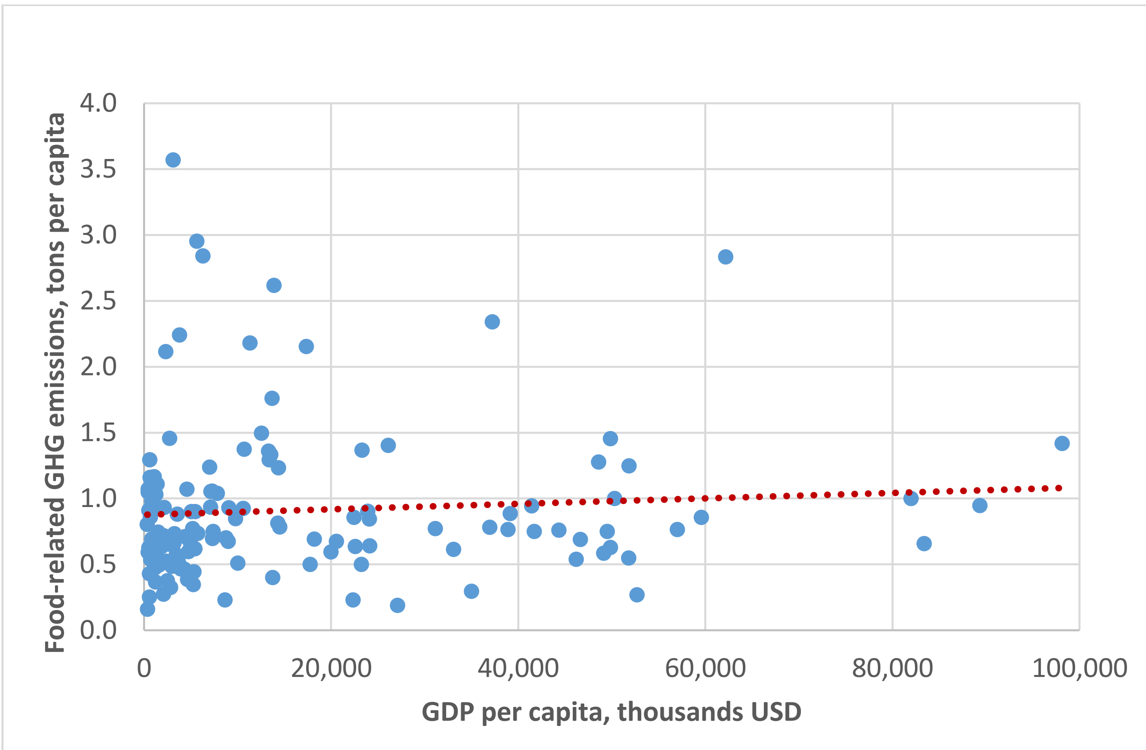

Figure 8. GHG emissions embodied into final households' consumption of food products vs GDP per capita by GTAP regions

Source: Authors' estimates based on Irfanoglu and van der Mensbrugghe (2015) and Aguiar et al. (2016).

Note: Botswana and Luxemburg are considered as outliers and are not reported on this figure.

To study the impacts of global greenhouse gas taxes on food products, we implement the range of CO_2 taxation scenarios using the Systematic Sensitivity Analysis (SSA) approach developed by Arndt and Pearson (1998). With this approach, we accompany central scenario ($35/ton CO_2-eq. tax rate) with 95% confidence intervals and indicate them using error bars. We use a triangular distribution for parameters variation and Stroud quadrature for approximation. To derive confidence intervals we assume normal distribution of the SCC values.

4. Preliminary results

Policy simulations suggest that imposition of the $35/ton CO_2-eq. tax on GHG emissions embodied into households' consumption of food products results in global non-CO_2 GHG emissions reduction of 108 Mt, which is equivalent to -0.8% change (Figure 9). In the absolute terms, around 64% of this reduction is associated with CH_4 emissions, while the rest is coming from N_2O emissions. In the relative terms, N_2O emissions though decrease at a higher pace than CH_4.

At the global level, both F-gases and CO_2 emissions are not impacted by taxes on food products. This brings aggregate GHG emissions reduction to 0.3% at the global level (Figure 9). Under varying carbon tax rate (between $15/ton CO_2-eq. and $55/ton CO_2-eq.) global GHG emissions could fall between 0.08% and 0.44%.

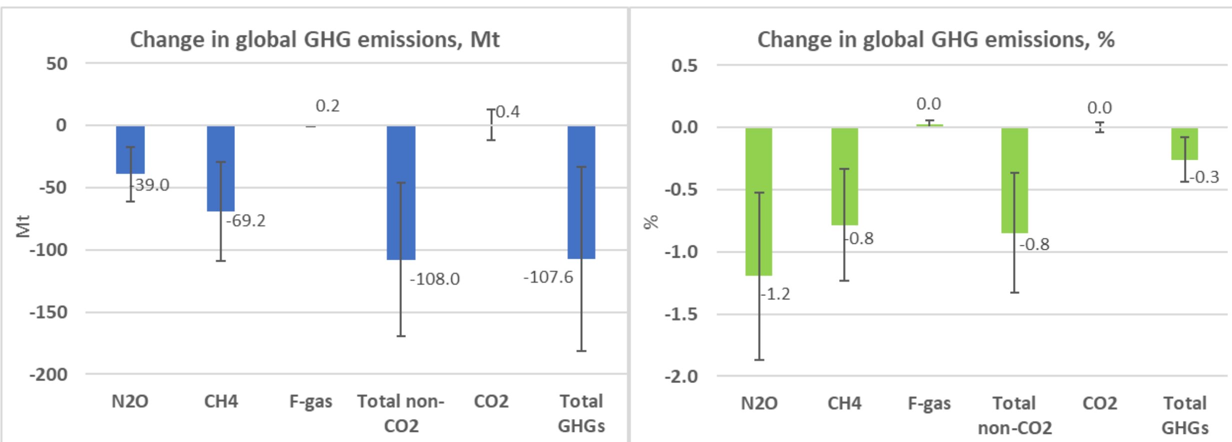

Figure 9. Changes in global GHG emissions following imposition of carbon tax on food products, relative to 2011 levels

Source: Estimated by authors.

Note: Error bars indicate 95% confidence intervals following variation in emission tax rates between $15/ton CO_2-eq. and $55/ton CO_2-eq. See Section 3 for more details.

Changes in non-CO_2 GHG emissions highly vary at the regional level, with largest reductions being observed in African and South American countries (Figure 10). In particular, in case of Kenya non-CO_2 GHG emissions fall by 5.4%, in Tanzania by 3.8%, Rest of Western Africa by 3.6% and Rest of Central Africa by 3.4%. In most advanced economies average non-CO_2 GHG reductions are between 0.5% and 1%. There are almost no country-cases with N_2O and CH_4 emission increases. The only exceptions include Rest of North America (N_2O emissions increase by 0.03%) and Malawi (CH_4 emissions increase by 0.08%), but in both cases aggregate GHG emissions decline following imposition of carbon taxes on food products.

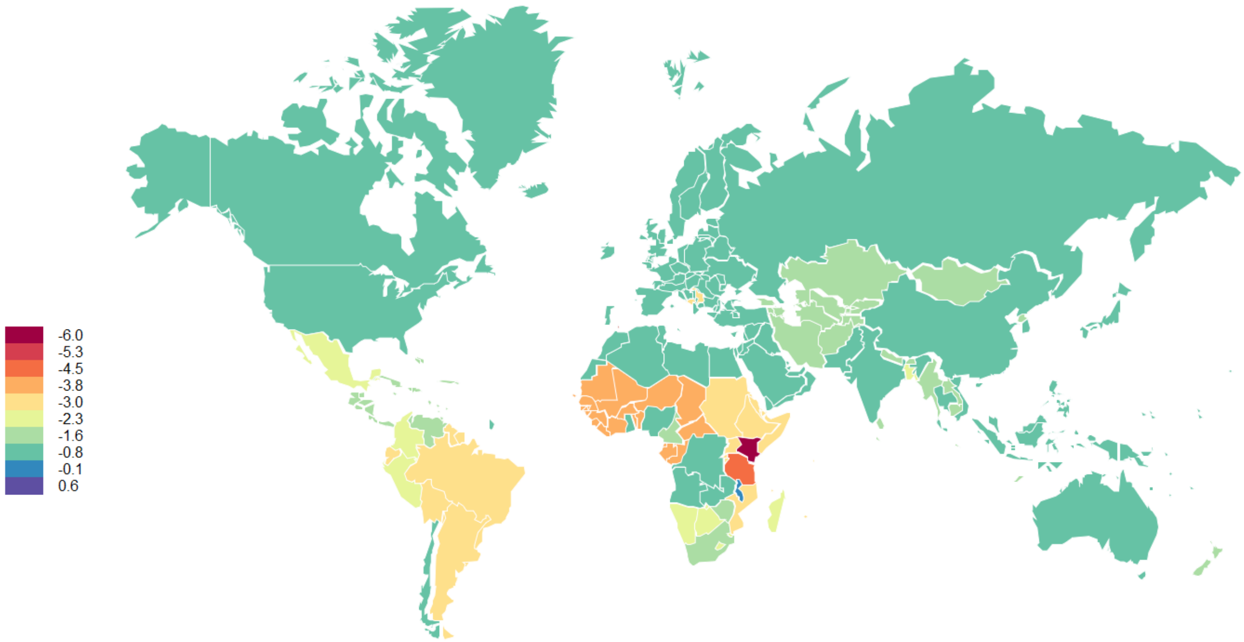

Figure 10. Changes in aggregate non-CO_2 GHG emissions by regions following imposition of carbon tax on food products, % relative to 2011 levels

Source: Estimated by authors.

Imposed carbon food tax does not result in any significant co-benefits for air pollution changes. In terms of both absolute and relative reductions, NH_3 emissions show the largest changes (-405 Mt and -0.7% respectively) (Figure 11). Emissions of other air pollutants decline by less than 0.1%. Performed sensitivity analysis shows high variation in estimated results. In all pollutant cases with an exception of NH_3, simulated changes in emission volumes change sign following variation of food carbon tax rate between \$15/ton CO_2-eq. and \$55/ton CO_2-eq., indicating that some leakage effects might occur (Figure 11). Global SO_2 emissions show insignificant increase even in the central case scenario. In general, in terms of air pollution changes at the global level, only NH_3 emissions experience measurable reduction following imposition of carbon food taxes, while other pollutants show mixed (undefined) trends.

At the regional level, changes in NH_3 emissions moderately vary by countries. Largest reductions are observed in Sub-Saharan Africa countries (-2.9% in Kenya, -2.1% in Madagascar, -1.9% in the Rest of Western Africa and -1.7% in Tanzania), as well as some Central Asian and Eastern European countries (Figure F.1).

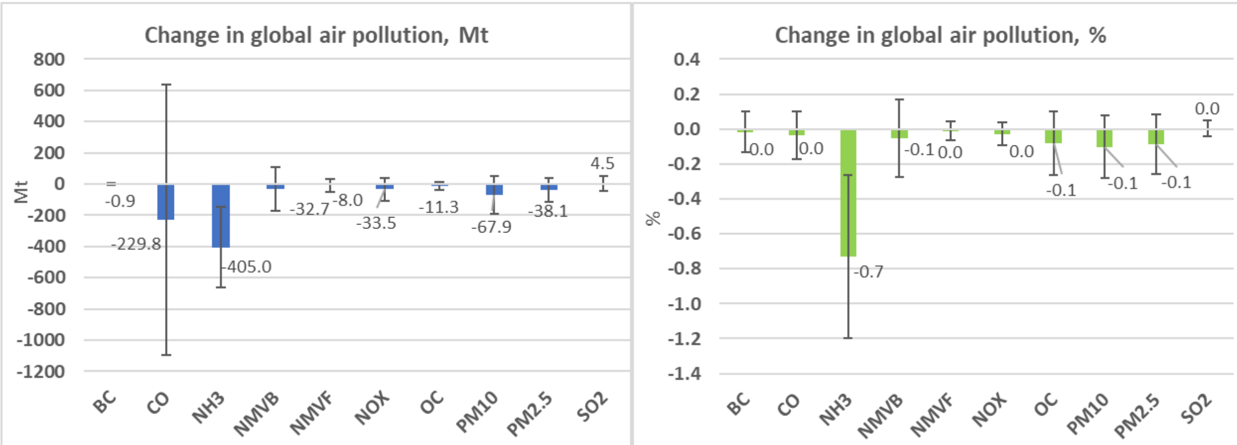

Figure 11. Changes in global air pollution levels following imposition of carbon tax on food products, % relative to 2011 levels

Source: Estimated by authors.

Note: Error bars indicate 95% confidence intervals following variation in emission tax rates between \$15/ton CO_2-eq. and \$55/ton CO_2-eq. See Section 3 for more details.

With increasing food prices following imposition of carbon food taxes, households adjust by both reducing volumes of food consumption and shifting from more to less carbon intensive commodities. In the case of first adjustment, countries with initially lower per capital calorific consumption experience higher relative reductions (Figure 12).

Number of Sub-Saharan Africa countries and regions, such as Zambia, Tanzania, Madagascar, Rest of South African Customs Union, Rest of Central Africa, etc., have reference levels of food consumption (in 2011) close or even below World Health Organization dietary recommendations (WHO, 2015). Further reductions in food consumption following imposition of food carbon taxes could significantly stress food supply in those regions, especially impacting the most vulnerable groups of households. In some of the aforementioned regional cases, absolute reductions in food supply could exceed 100-120 kcal/capita/day (Figure G.1). Similar trends and vulnerability issues are true for the protein supply, with an addition of some large absolute reductions in South American countries (Figure G.3).

In case of fat supply, some developed countries (Australia, Canada, United States) experience similar or even higher absolute reductions than most developing economies. Considering high reference values of per capita fat consumption in the advanced economies (in most cases, above WHO recommended levels), such reductions could be considered as a move towards healthier diet.

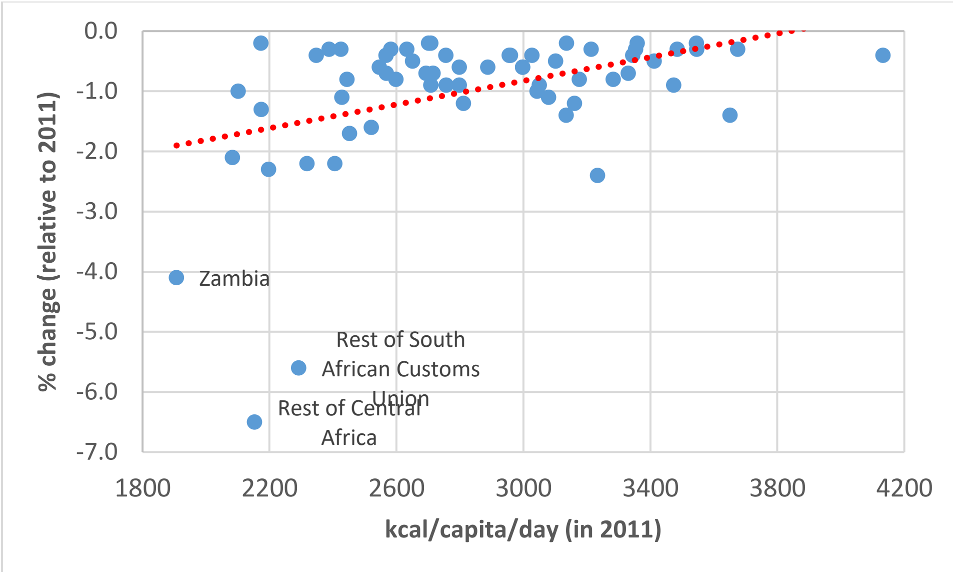

Figure 12. Changes in food supply by regions following imposition of carbon tax on food products, % relative to 2011 levels

Source: Estimated by authors.

Note: Each point corresponds to one aggregate region. See Appendix D for the list of regions.

At the sectoral level, highest reductions in both output and food supply are observed in the most carbon intensive sectors, namely Cattle meat, Raw milk, Paddy rice and Processed rice (Figure 13). In the case of cattle meat food supply falls by 3.5% in the central case of \$35/ton CO_2-eq. tax rate and could fall by 4.2% if higher rate of \$55/ton CO_2-eq. would be applied. There are no leakage effects observed in terms of food supply increase by the sectors with low emission tax rates, such as Beverages and tobacco, Food products nec, Vegetables, fruits, nuts and Fish (all these sectors face global average carbon tax rates of 2.6% or lower). These sectors also show food supply decrease, though on average below 0.6%-0.7% at a global level.

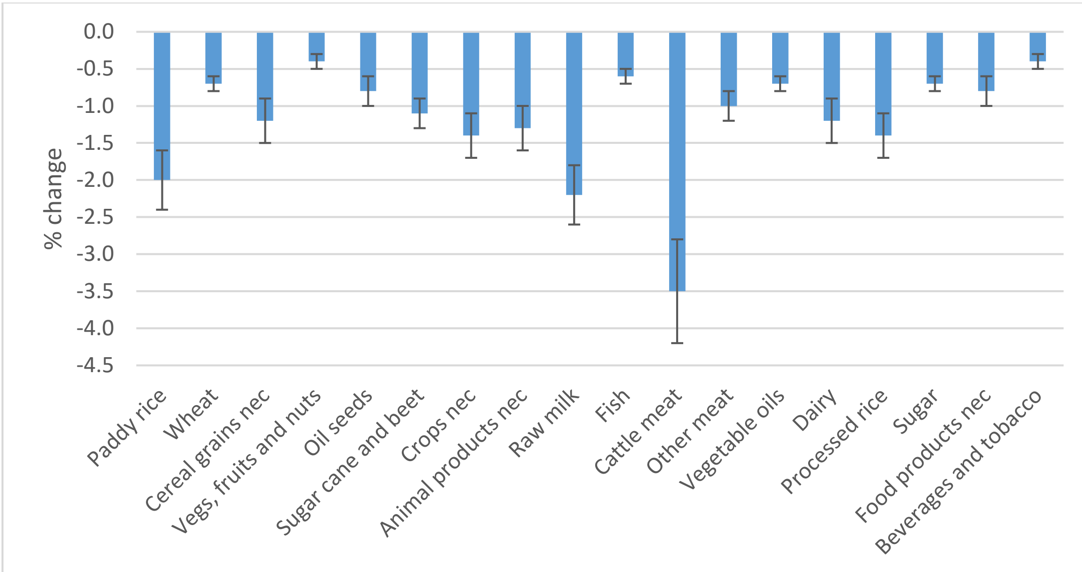

Figure 13. Changes in global food supply by sectors, % relative to 2011 levels

Source: Estimated by authors.

Note: Error bars indicate 95% confidence intervals following variation in emission tax rates between \$15/ton CO_2-eq. and \$55/ton CO_2-eq. See Section 3 for more details.

Imposition of \$35/ton CO_2-eq. tax rate on GHG emissions embodied into final households' consumption has an insignificant impact on global welfare, as it declines by around 0.002% (-\$1.4 billion). More significant changes in welfare are observed at the regional level, though variation by regions is relatively moderate (Figure H.1). Sub-Saharan Africa countries experience the largest reductions, exceeding -0.4% in the cases of Uganda and Tanzania.

In terms of welfare cost of GHG emission reductions, a global average equals 13.4 \$/ton CO_2-eq. We estimate this cost by dividing changes in aggregate GHG emissions by welfare changes. Negative estimates of this indicator suggest that welfare is increasing, GHG emissions are falling. At the regional level, welfare cost of GHG emission reductions highly vary (Figure H.2). North African, Middle Eastern and EU countries show negative welfare cost of GHG emission cuts. In selected regions and countries, such as Argentina, Canada, Chili, Ghana, Russia, Thailand, Ukraine, Zambia, etc., these costs could exceed \$100/ton CO_2-eq. At the same time, considering low relative and absolute changes in GHG emissions, these numbers might not be representative in case of impacts upscaling.

5. Conclusions

Agricultural and food systems are contributing over 25% of global GHG emissions. Demographic changes and increasing income are expected to further push the global diet towards more meat-oriented and emission-intensive food items, as a result, agricultural GHG emissions could significantly increase in the long-run. But even without significant shifts in the global diet, food-related emissions could grow by over 70% between 2000 and 2070 (Hedenus et al., 2014), which would make it almost impossible to keep the global temperature increase *well below 2°C*, as desired by the Paris Climate Agreement. Reducing the food-related GHG emissions is a crucial component in meeting the stringent climate change targets.

Therefore, the focus of this paper is to provide a global assessment of food-related GHG emissions taxation. For this purpose, we use a multi-sector multi-region CGE framework, based on the GTAP model. We further improve and complement the GTAP framework in several ways. First, we develop the GTAP database (2011 reference year) with updated agricultural production targeting for 133 regions. Second, we develop a GTAP-consistent food balance sheets with dietary and nutritional information covering all 141 regions in the database. This allows us to track changes in the per capita food supply quantity, as well as protein and fat supply levels by country. Finally, we complement the GTAP-E modelling framework by including the non-CO_2 GHG emissions and air pollution accounts, in addition to the CO_2 emissions already embedded into the model.

We explore the scenario with the carbon tax value of \$35/ton CO_2-eq. (\$2010 PPP). Based on the volumes of GHG emissions embodied into food consumption by households, we estimate food consumption tax rates corresponding to the carbon tax value. We further use the systematic sensitivity analysis approach and vary carbon tax between \$15/ton CO_2-eq. and \$55/ton CO_2-eq.

Our simulations suggest that in the central case (carbon tax value of \$35/ton CO_2-eq.), global non-CO_2 GHG emissions decrease by 0.85% (0.4%-1.3% reduction under varying tax rates), while global GHG emissions fall by around 0.3%. These reductions are highly variable among regions, with the highest cuts observed in African and South American countries (reaching up to 4%-5% in some cases).

Imposed carbon food tax does not result in any significant co-benefits for air pollution changes. In terms of both absolute and relative reductions, NH_3 emissions show the largest changes (-405 Mt and -0.7% respectively), while emissions of other air pollutants decline by less than 0.1%. Performed sensitivity analysis shows high variation in estimated results for air pollution changes.

With increasing food prices following imposition of carbon food taxes, households adjust by both reducing volumes of food consumption and shifting from more to less carbon intensive commodities. Countries with initially lower per capita calorific consumption experience higher relative reductions in food supply. In the number of Sub-Saharan Africa countries and regions, this could result in per capita food consumption falling below WHO recommended levels, especially impacting the most vulnerable groups of households. Similar trends and vulnerability issues are true for the protein supply, with an addition of some large absolute reductions in South American countries.

In case of fat supply, some developed countries (Australia, Canada, United States) experience similar or even higher absolute reductions than most developing economies. Considering high reference values of per capita fat consumption in the advanced economies (in most cases, above WHO recommended levels), such reductions could be considered as a move towards healthier diet.

At the sectoral level, highest reductions in both output and food supply are observed in the most carbon intensive sectors, namely Cattle meat, Raw milk, Paddy rice and Processed rice. In the case of cattle meat food supply falls by 3.5% in the central case of \$35/ton CO_2-eq. tax rate and could fall by 4.2% if higher rate of \$55/ton CO_2-eq. would be applied.

There is no significant impact on global welfare, as it declines by around 0.002% (-\$1.4 billion). At the regional level, Sub-Saharan Africa countries experience the largest reductions, exceeding -0.4% in the cases of Uganda and Tanzania. In terms of welfare cost of GHG emission reductions, a global average equals 13.4 \$/ton CO_2-eq. North African, Middle Eastern and EU countries show negative welfare cost of GHG emission cuts, while in the number of countries these costs could exceed \$100/ton CO_2-eq. At the same time, considering low relative and absolute changes in GHG emissions, these numbers might not be representative in case of impacts upscaling.

Our results suggest substantially lower GHG reductions from food taxation than some of the existing literature. In particular, Springmann et al. (2016) estimated that \$52/ton CO_2-eq. tax on food products could reduce agriculture and food related GHG emissions by 9.3% (1000 Gt-CO_2-eq.) in 2020. Both methodological approach and scenarios explored in our paper differ from those used by Springman et al. (2016). In particular, Springman et al. (2016) use partial equilibrium model (do not allow for interactions external to food sectors) and represents a large number of food commodities (potentially this could allow for higher substitution away from carbon intensive commodities). They also estimate changes in the year 2020 (higher GHG emissions base), while we focus on 2011. Nevertheless, differences in our results seem to be large enough to be explored in more details.

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Appendix A. Mapping between GTAP sectors and FBS categories

No.	FBS code	FBS category name	GTAP sector	GTAP primary sector (for mapping)
1	**2**	**3**	**4**	**5**
1	2511	Wheat and products	wht, ofd	wht
2	2513	Barley and products	gro, ofd	gro
3	2514	Maize and products	gro, ofd	gro
4	2515	Rye and products	gro, ofd	gro
5	2516	Oats	gro, ofd	gro
6	2517	Millet and products	gro, ofd	gro
7	2518	Sorghum and products	gro, ofd	gro
8	2520	Cereals, Other	gro, ofd	gro
9	2531	Potatoes and products	v_f, ofd	gro
10	2532	Cassava and products	v_f, ofd	gro
11	2533	Sweet potatoes	v_f	-
12	2534	Roots, Other	v_f, ofd	v_f
13	2535	Yams	v_f	-
14	2536	Sugar cane	c_b	-
15	2537	Sugar beet	c_b	-
16	2541	Sugar non-centrifugal	sgr	-
17	2542	Sugar (Raw Equivalent)	sgr	-
18	2543	Sweeteners, Other	ofd	-
19	2546	Beans	osd	-
20	2547	Peas	osd	-
21	2549	Pulses, Other and products	v_f, ofd	v_f
22	2551	Nuts and products	v_f, ofd	v_f
23	2555	Soyabeans	osd	-
24	2556	Groundnuts (Shelled Eq)	osd, ofd	osd
25	2557	Sunflower seed	osd	-
26	2558	Rape and Mustardseed	osd, ofd	osd
27	2559	Cottonseed	osd	-
28	2560	Coconuts - Incl Copra	osd, ofd	osd
29	2561	Sesame seed	osd	-

No.	FBS code	FBS category name	GTAP sector	GTAP primary sector (for mapping)
1	2	3	4	5
30	2562	Palm kernels	osd, vol	osd
31	2563	Olives (including preserved)	osd, ofd	osd
32	2570	Oilcrops, Other	osd	-
33	2571	Soyabean Oil	vol	-
34	2572	Groundnut Oil	vol	-
35	2573	Sunflowerseed Oil	vol	-
36	2574	Rape and Mustard Oil	vol	-
37	2575	Cottonseed Oil	vol	-
38	2576	Palmkernel Oil	vol	-
39	2577	Palm Oil	vol	-
40	2578	Coconut Oil	vol	-
41	2579	Sesameseed Oil	vol	-
42	2580	Olive Oil	vol	-
43	2581	Ricebran Oil	vol	-
44	2582	Maize Germ Oil	vol	-
45	2586	Oilcrops Oil, Other	vol, ofd	-
46	2601	Tomatoes and products	v_f, ofd	v_f
47	2602	Onions	v_f	-
48	2605	Vegetables, Other	v_f, ocr, ofd	v_f
49	2611	Oranges, Mandarines	v_f, ofd	v_f
50	2612	Lemons, Limes and products	v_f, ofd	v_f
51	2613	Grapefruit and products	v_f, ofd	v_f
52	2614	Citrus, Other	v_f, ofd	v_f
53	2615	Bananas	v_f	-
54	2616	Plantains	v_f	-
55	2617	Apples and products	v_f, ofd	v_f
56	2618	Pineapples and products	v_f, ofd	v_f
57	2619	Dates	v_f	-
58	2620	Grapes and products (excl wine)	v_f, ofd	v_f
59	2625	Fruits, Other	v_f, ofd	v_f

No.	FBS code	FBS category name	GTAP sector	GTAP primary sector (for mapping)
1	**2**	**3**	**4**	**5**
60	2630	Coffee and products	ofd	-
61	2633	Cocoa Beans and products	ofd	-
62	2635	Tea (including mate)	ocr, ofd	ocr
63	2640	Pepper	ocr	-
64	2641	Pimento	ocr	-
65	2642	Cloves	ocr	-
66	2645	Spices, Other	ocr	-
67	2655	Wine	b_t	-
68	2656	Beer	b_t	-
69	2657	Beverages, Fermented	b_t	-
70	2658	Beverages, Alcoholic	b_t	-
71	2659	Alcohol, Non-Food	NA	NA
72	2680	Infant food	ofd	-
73	2731	Bovine Meat	cmt	-
74	2732	Mutton & Goat Meat	cmt	-
75	2733	Pigmeat	omt	-
76	2734	Poultry Meat	omt	-
77	2735	Meat, Other	omt	-
78	2736	Offals, Edible	cmt, omt	-
79	2737	Fats, Animals, Raw	vol	-
80	2740	Butter, Ghee	mil	-
81	2743	Cream	mil	-
82	2744	Eggs	oap	-
83	2745	Honey	oap	-
84	2761	Freshwater Fish	fsh, ofd	fsh
85	2762	Demersal Fish	fsh, ofd	fsh
86	2763	Pelagic Fish	fsh, ofd	fsh
87	2764	Marine Fish, Other	fsh, ofd	fsh
88	2765	Crustaceans	fsh, ofd	fsh
89	2766	Cephalopods	fsh, ofd	fsh
90	2767	Molluscs, Other	fsh, ofd	fsh

No.	FBS code	FBS category name	GTAP sector	GTAP primary sector (for mapping)
1	**2**	**3**	**4**	**5**
91	2768	Meat, Aquatic Mammals	omt	-
92	2769	Aquatic Animals, Others	fsh, ofd	fsh
93	2775	Aquatic Plants	fsh, ofd	fsh
94	2781	Fish, Body Oil	vol	-
95	2782	Fish, Liver Oil	vol	-
96	2805	Rice (Milled Equivalent)	pdr, pcr	pdr
97	2848	Milk - Excluding Butter	rmk, mil	-
98	2899	Miscellaneous	ofd	-

Source: Authors.

Appendix B. Mean (world average) and standard deviation estimates for food, fat and protein supply by GTAP sectors

No.	GTAP sector	Food supply (kcal/capita/day)		Fat supply (g/capita/day)		Protein supply (g/capita/day)	
		Mean	SD	Mean	SD	Mean	SD
1	Paddy rice	87.2	158.2	0.2	0.5	1.7	3.3
2	Wheat	271.7	297.2	1.4	1.7	8.1	8.9
3	Cereal grains nec	269.6	312.4	1.8	2.7	6.2	7.3
4	Vegs, fruits and nuts	216.8	137.1	2.4	1.9	5.6	3.1
5	Oil seeds	67.9	64.4	2.8	3.2	3.7	3.7
6	Sugar cane and beet	1.9	5.7	0.0	0.0	0.0	0.0
7	Crops nec	10.2	11.2	0.4	0.4	0.5	0.5
8	Animal products nec	31.1	21.7	2.0	1.4	2.2	1.6
9	Raw milk	20.9	32.9	1.2	1.9	1.2	1.9
10	Fish	20.2	19.9	0.7	0.7	3.1	3.1
11	Cattle meat	76.4	68.5	5.4	5.2	6.5	5.2
12	Other meat	174.2	127.3	13.3	10.5	12.6	8.5
13	Vegetable oils	341.3	172.5	37.8	19.2	0.4	0.4
14	Dairy	198.4	150.0	12.9	10.6	10.0	7.7
15	Processed rice	211.4	341.1	0.5	1.0	4.1	6.6
16	Sugar	259.2	125.0	0.0	0.0	0.0	0.1
17	Food products nec	541.8	352.6	6.3	4.4	16.3	11.0
18	Beverages and tobacco	89.2	74.7	0.0	0.1	0.5	0.5
19	***All sectors***	***2889.1***	***465.0***	***88.6***	***36.1***	***82.8***	***20.2***

Source: Authors' estimates based on Aguiar et al. (2016), Chepeliev and Aguiar (2018) and FAO (2018).

Appendix C. Sectoral aggregation

No.	Aggregate sector code	Aggregate sector description	GTAP sector
1	pdr	Paddy rice	pdr
2	wht	Wheat	wht
3	gro	Cereal grains nec	gro
4	v_f	Vegetables, fruit, nuts	v_f
5	osd	Oil seeds	osd
6	c_b	Sugar cane, sugar beet	c_b
7	pfb	Plant-based fibers	pfb
8	ocr	Crops nec	ocr
9	ctl	Cattle, sheep, goats ,horses	ctl
10	oap	Animal products nec	oap
11	rmk	Raw milk	rmk
12	wol	Wool, silk-worm cocoons	wol
13	frs	Forestry	frs
14	fsh	Fishing	fsh
15	coa	Coal	coa
16	oil	Oil	oil
17	gas	Gas and gas distribution	gas gdt
18	omn	Minerals nec	omn
19	cmt	Meat: cattle, sheep, goats, horse	cmt
20	omt	Meat products nec	omt
21	vol	Vegetable oils and fats	vol
22	mil	Dairy products	mil
23	pcr	Processed rice	pcr
24	sgr	Sugar	sgr
25	ofd	Food products nec	ofd
26	b_t	Beverages and tobacco products	b_t
27	p_c	Petroleum, coal products	p_c
28	ke5	Energy intensive industries	crp nmm i_s nfm fmp
29	xma	Other manufacturing	tex wap lea lum ppp mvh otn ele ome omf
30	ely	Electricity	ely
31	wtr	Water distribution	wtr
32	cns	Construction	cns
33	trd	Trade	trd
34	trn	Transportation	otp wtp atp
35	osv	Other services	cmn ofi isr obs ros osg dwe

Source: Authors.

Appendix D. Regional aggregation

No.	Aggregate region code	Aggregate region description	GTAP region
1	aus	Australia	aus
2	nzl	New Zealand	nzl
3	xoc	Rest of Oceania	xoc
4	chn	China	chn
5	xea	Rest of East Asia	hkg mng xea brn khm lao sgp xse
6	jpn	Japan	jpn
7	kor	Korea	kor
8	twn	Taiwan	twn
9	idn	Indonesia	idn
10	mys	Malaysia	mys
11	phl	Philippines	phl
12	tha	Thailand	tha
13	vnm	Viet Nam	vnm
14	bgd	Bangladesh	bgd
15	ind	India	ind
16	xsa	Rest of South Asia	npl lka xsa
17	pak	Pakistan	pak
18	can	Canada	can
19	usa	United States of America	usa
20	mex	Mexico	mex
21	xna	Rest of North America	xna
22	arg	Argentina	arg
23	xsm	Rest of South America	bol ecu pry ury xsm
24	bra	Brazil	bra
25	chl	Chile	chl
26	col	Colombia	col
27	per	Peru	per
28	ven	Venezuela	ven
29	xca	Rest of Central America	cri gtm hnd nic pan slv xca
30	xcb	Caribbean	dom jam pri tto xcb
31	eur	EU28	aut bel cyp cze dnk est fin fra deu grc hun irl ita lva ltu lux mlt nld pol prt svk svn esp swe gbr bgr hrv rou
32	xeu	Rest of Europe	alb blr xee xer
33	xef	Rest of EFTA	che nor xef
34	rus	Russian Federation	rus
35	ukr	Ukraine	ukr
36	xsu	Rest of Former Soviet Union	kaz kgz tjk xsu arm aze geo

No.	Aggregate region code	Aggregate region description	GTAP region
37	xws	Rest of Western Asia	bhr kwt omn qat are xws
38	irn	Iran Islamic Republic of	irn
39	isr	Israel	isr
40	jor	Jordan	jor
41	sau	Saudi Arabia	sau
42	tur	Turkey	tur
43	egy	Egypt	egy
44	mar	Morocco	mar
45	tun	Tunisia	tun
46	xnf	Rest of North Africa	xnf
47	xwf	Rest of Western Africa	ben bfa civ gin sen tgo xwf
48	cmr	Cameroon	cmr
49	gha	Ghana	gha
50	nga	Nigeria	nga
51	xcf	Central Africa	xcf
52	xac	South Central Africa	xac
53	eth	Ethiopia	eth
54	ken	Kenya	ken
55	mdg	Madagascar	mdg
56	mwi	Malawi	mwi
57	xec	Rest of Eastern Africa	mus moz rwa xec
58	tza	Tanzania	tza
59	uga	Uganda	uga
60	zmb	Zambia	zmb
61	zwe	Zimbabwe	zwe
62	xsc	Rest of South African Customs	bwa nam xsc
63	zaf	South Africa	zaf
64	xtw	Rest of the World	xtw

Source: Authors.

Appendix E. Sectoral and regional GHG emission profiles

Table E.1. GHG emissions embodied into final households' consumption of food products by aggregate regions

No.	Region code	Region name	Emissions, Mt of CO2-eq.
1	chn	China	833.8
2	ind	India	757.8
3	usa	United States of America	453.2
4	eur	EU28	430.9
5	bra	Brazil	294.8
6	rus	Russian Federation	194.5
7	idn	Indonesia	140
8	xwf	Rest of Western Africa	125
9	mex	Mexico	101.4
10	irn	Iran Islamic Republic of	93.5
11	pak	Pakistan	92.6
12	xea	Rest of East Asia	91.8
13	xsu	Rest of Former Soviet Union	91.1
14	bgd	Bangladesh	89.2
15	xec	Rest of Eastern Africa	84.5
16	eth	Ethiopia	71.9
17	arg	Argentina	71.7
18	jpn	Japan	69.1
19	tur	Turkey	67.6
20	aus	Australia	63.2
21	xac	South Central Africa	62.8
22	nga	Nigeria	61.9
23	xsm	Rest of South America	60.4
24	vnm	Viet Nam	59.4
25	xws	Rest of Western Asia	55.6
26	zaf	South Africa	53.7
27	tha	Thailand	51.4
28	phl	Philippines	49.9
29	xeu	Rest of Europe	47.4
30	xsa	Rest of South Asia	46.3
31	col	Colombia	44.1
32	can	Canada	42.8
33	tza	Tanzania	42.3
34	ken	Kenya	41.2
35	ven	Venezuela	40.6
36	ukr	Ukraine	40.3
37	egy	Egypt	38.7
38	xcf	Central Africa	33.8
39	kor	Korea	31.9
40	xca	Rest of Central America	29.4

No.	Region code	Region name	Emissions, Mt of CO2-eq.
41	xcb	Caribbean	25.7
42	xsc	Rest of South African Customs	25.7
43	sau	Saudi Arabia	23.5
44	mdg	Madagascar	22.8
45	per	Peru	21.8
46	uga	Uganda	20.8
47	mar	Morocco	20.7
48	xnf	Rest of North Africa	15.4
49	zmb	Zambia	15.1
50	mys	Malaysia	14.7
51	twn	Taiwan	13.8
52	chl	Chile	13.6
53	xef	Rest of EFTA	12.7
54	gha	Ghana	12.3
55	zwe	Zimbabwe	12.1
56	nzl	New Zealand	10.3
57	cmr	Cameroon	10.1
58	xoc	Rest of Oceania	7.2
59	tun	Tunisia	5
60	isr	Israel	4.8
61	mwi	Malawi	2.5
62	jor	Jordan	2.4
63	xna	Rest of North America	0.1
64	xtw	Rest of the World	0

Source: Authors' estimates based on Irfanoglu and van der Mensbrugghe (2015) and Aguiar et al. (2016).

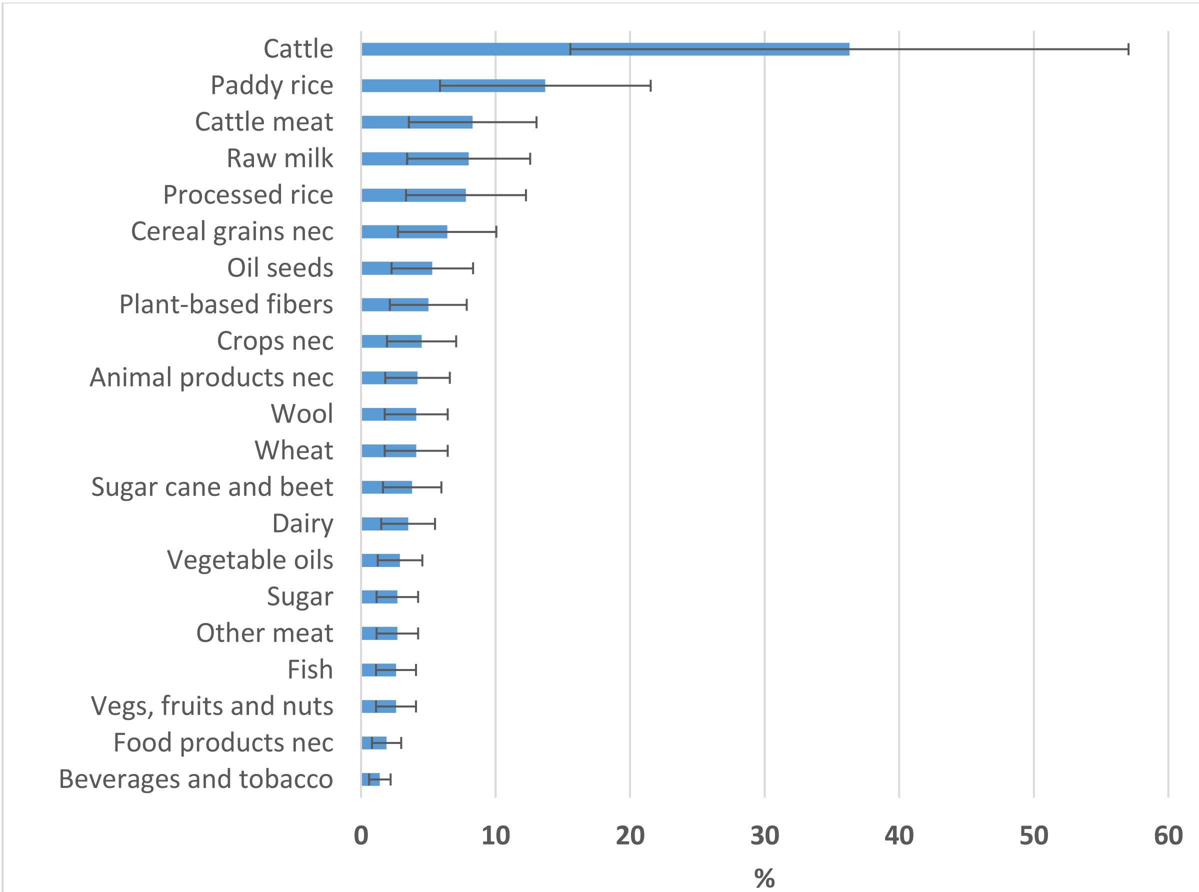

Figure E.1. Global average final consumption tax rates corresponding to $35/ton CO_2-eq. tax on GHG emissions embodied into final households' consumption of food products, %

Source: Estimated by authors.

Note: Error bars indicate tax rates that correspond to $15/ton CO_2-eq. (lower bound) and $55/ton CO_2-eq. (upper bound).

Appendix F. Changes in air pollution levels following imposition of carbon tax on food products

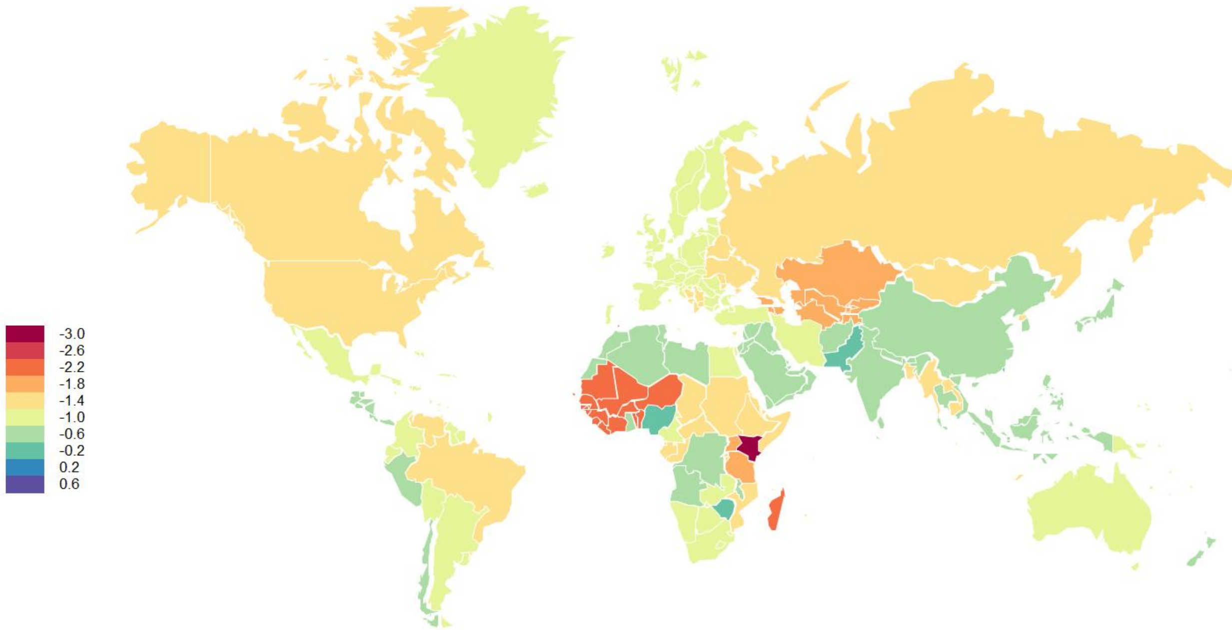

Figure F.1. Changes in NH_3 emissions by regions following imposition of carbon tax on food products, % relative to 2011 levels

Source: Estimated by authors.

Appendix G. Nutritional impacts of the carbon tax on food products

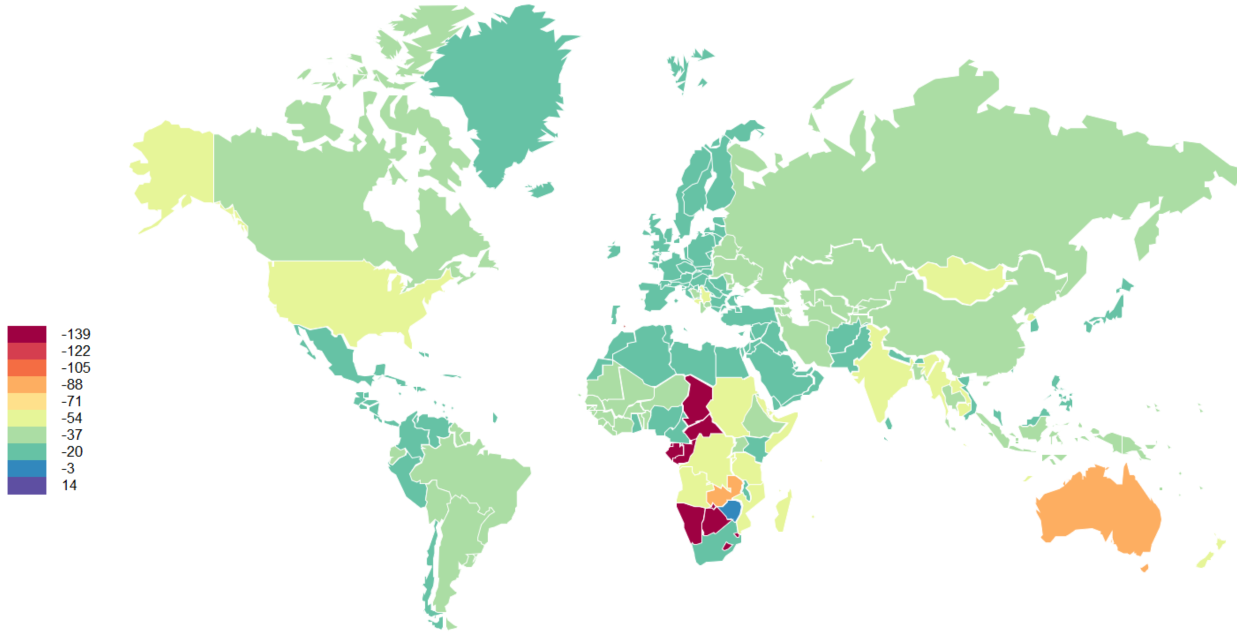

Figure G.1. Changes in food consumption by regions, kcal/capita/day
Source: Estimated by authors.

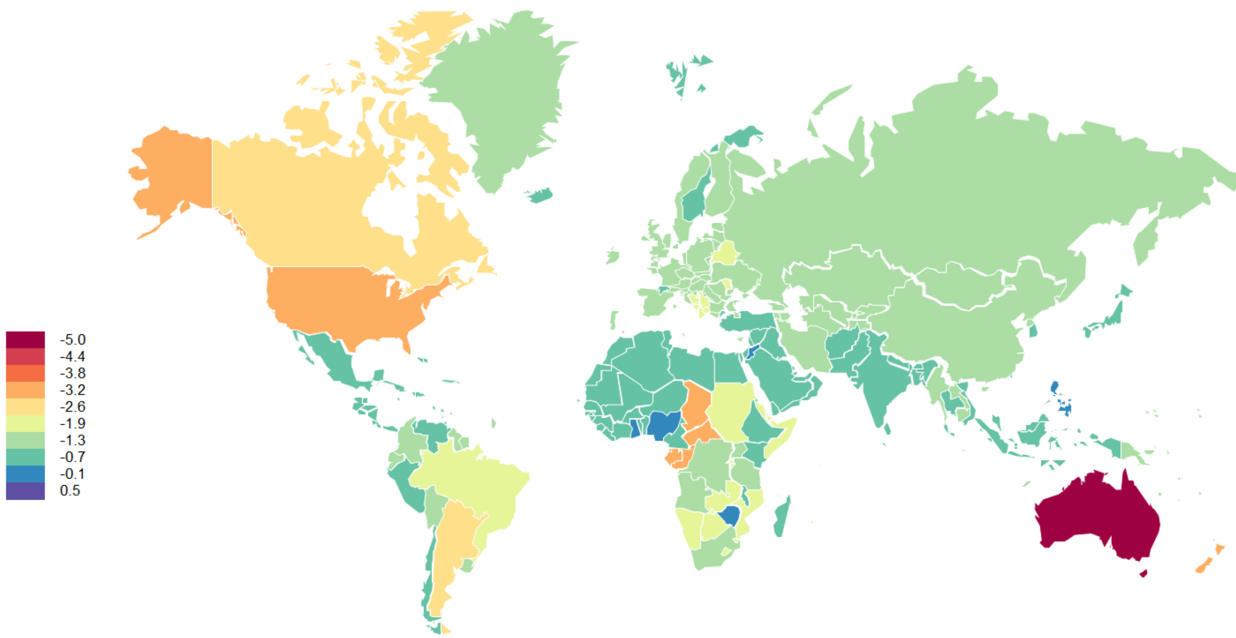

Figure G.2. Changes in fat supply by regions, g/capita/day
Source: Estimated by authors.

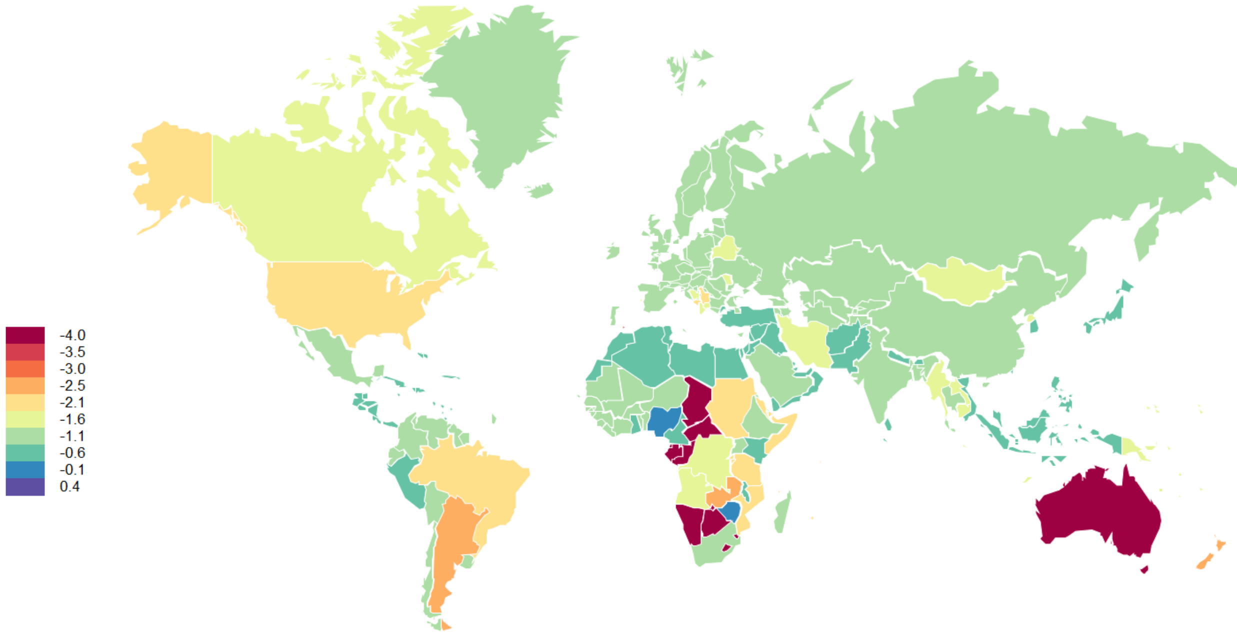

Figure G.3. Changes in protein supply by regions, g/capita/day
Source: Estimated by authors.

Appendix H. Welfare impacts of the carbon tax on food products

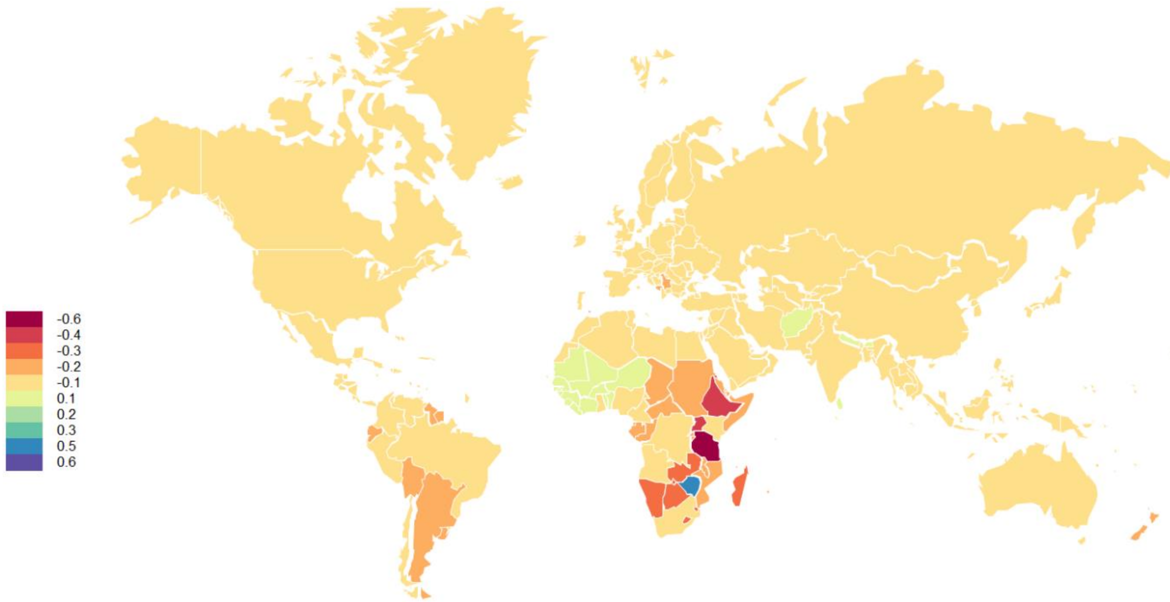

Figure H.1. Welfare impacts of the carbon tax on food products, % change relative to 2011 levels

Source: Estimated by authors.

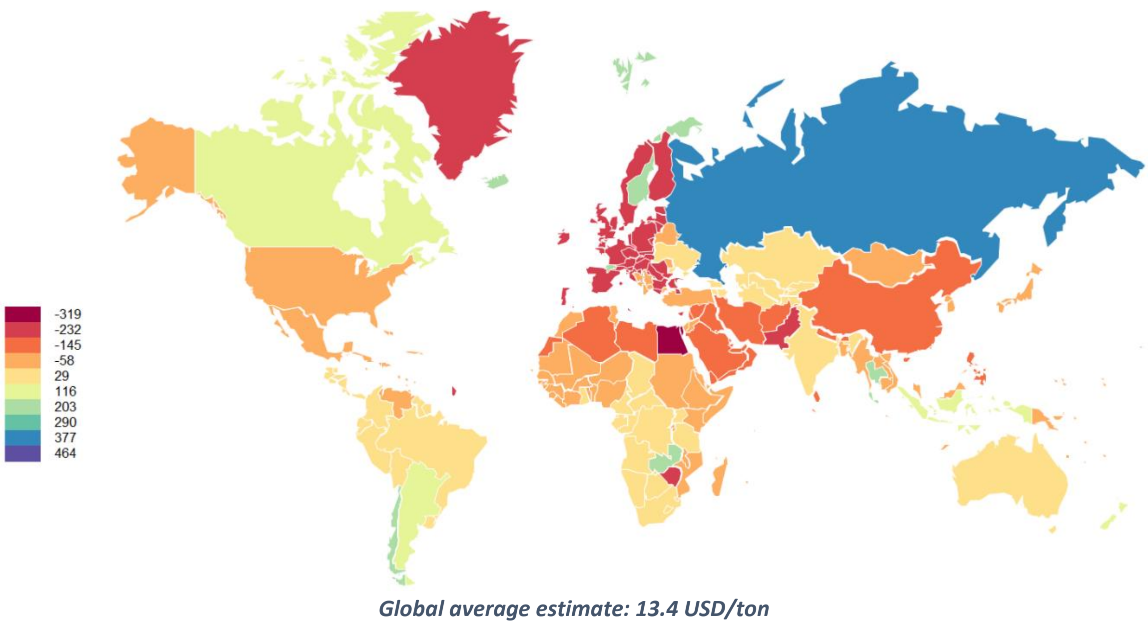

Figure H.2. Welfare costs per ton of aggregate GHG emissions reduction, \$/ton CO_2-eq.

Source: Estimated by authors.

Note: Only countries with aggregate GHG emissions reduction below -0.1% are used to estimate the cost of reduction (otherwise a default value of "0" is reported). Negative values imply that welfare is increasing, while GHG emissions are falling.