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Carbon leakage and limited efficiency of greenhouse gas taxes on food products

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ABSTRACT

Greenhouse gas emission (GHGE) taxes on food products have recently been proposed as means to help reduce agricultural emissions. Numerous authors have calculated potential GHGE reductions in case such a tax was implemented in certain countries or regions. They did however assume a reduced production of GHGE-intense foods equal to the decline in demand induced by the tax. This omits however possible increases of net-exports that might offset such a demand reduction. Herein, the market dynamic behind this so-called “emission leakage” is explained and its effect quantified for a greenhouse gas tax in the European Union. We use the European Forest and Agricultural Sector Optimization Model for the quantitative analysis and simulate a greenhouse gas tax on all food products, based on their individual emission levels. The partial equilibrium model covers all world regions and hence the tax's effects on international trade of agricultural commodities can be examined. It was found that 43% of the greenhouse gas reduction indicted by a domestic consumption reduction is lost through emission leakage. This already includes the mitigating effects of a production shift from inefficient to efficient producers that is another consequence of increased exports from the European Union. A greenhouse gas emission tax on food products is hence much less efficient than previously proposed, if it is not introduced globally or trade is not restricted.

1. Introduction

Agriculture largely contributes to greenhouse gas emission (GHGE) and therefore climate change. In 2010, an estimated 24% of all anthropogenic GHGE were directly linked to agriculture and forestry - most of which emerge during deforestation, enteric fermentation in livestock as well as manure management and application or the energy use during agricultural activities. Further emissions can be attributed indirectly to the agriculture and forestry sector. They involve the production and transport of agricultural inputs such as fertilizers and crop protection products. Considering that deforestation is mostly carried out to increase pastures or cropland, it follows that over a quarter of global GHGE stem from agricultural activities (IPCC, 2014).

Moreover, because large shares of the world's crop production are used as animal feed, livestock is the largest GHG emitter within agriculture. An estimated 18% of all global GHGE are linked to livestock (Steinfeld et al., 2006). Ruminant animals including cattle, sheep, and goats release most GHGE especially from enteric fermentation (methane), but also due to a lower feed conversion efficiency and the large amounts of manure they produce (mostly methane and nitrous oxide). On average, beef, mutton, and goat meats are by far the foods with the highest specific GHGE followed by pork. The GHGE released during meat production are multiple times higher per-calorie than the emissions of vegetal foods. Numerous authors have elaborated on this with similar results, e.g. (Audsley et al., 2009; Cederberg et al., 2013; de Vries and de Boer, 2010; Gonzalez et al., 2011; Lesschen et al., 2011; Meier and Christen, 2013).

Given the importance of agricultural GHGE, numerous studies have explored possible emission abatement options. Technical mitigation approaches including enhanced carbon sequestration, optimized nutrient use (e.g. precision farming for reduced

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synthetic inputs), improved productivity, improving the use of outputs (e.g. waste reduction), or reducing the GHGE of agricultural inputs (e.g. through using renewable energy), can decrease the emissions per unit of produced food. However, production related abatement measures might not be sufficient, especially when considering a growing and enriching world population. Structural changes in demand and consequentially production are hence needed, i.e. a reduced demand for high-emission foods (Garnett, 2011).

Economic approaches to reduce agricultural GHGE include the taxation of produce according to their specific emissions. Prices for GHGE-intense foods would increase relative to others and trigger a shift in consumption leading to lower GHGE. Several authors have studied such a tax in recent years and examined its efficiency. Wirsenius et al. found that a GHGE tax on animal-sourced foods could lead to a 7% reduction in agricultural GHGE in the EU at a tax rate of 60 EUR t^{-1} CO_2-eqivalent (CO_2e). 80% of this effect could be captured by taxing the consumption of ruminant meat alone (Wirsenius et al., 2011). Edjabou and Smed found similarly that a tax of around 60 EUR t^{-1} CO_2e on various foods could lead to a 4.0–7.9% decrease in GHGE from Danish agriculture – up to 19.4% are possible. They also found that total taxes on foods do not have to be increased to achieve this reduction. A rearrangement of current taxes yielding the same total tax revenue would suffice (Edjabou and Smed, 2013). Säll and Gren found that an environmental tax on livestock products covering GHG, nitrogen, phosphorus, and ammonia emissions could lower GHGE from agriculture in Sweden by up to 12% (Säll and Gren, 2015). Abadie et al. found that GHGE taxes can lead to a 10% emission reduction in Norway, with price increases of up to 40% for GHG-intense products (Abadie et al., 2016). Caillavet et al. found a 7.5% GHGE reduction for French diets, if animal-based foods were taxed such that prices increase by 20% (Caillavet et al., 2016). Chalmers et al. found that Scottish emissions related to meat production could be reduced by 10.5% through meat consumption taxes. Prices of meat would increase by up to 13% in this case. The demand reduction took place irrespective of the socioeconomic group (Chalmers et al., 2016). Springmann et al. found a 9.3% reduction in agricultural GHGE, if a tax of 52 USD t^{-1} CO_2e was introduced globally on food (Springmann et al., 2017). Kehlbacher et al. found that already a tax on food of just 2.84 GBP t^{-1} CO_2e (ca. 3.2 EUR) could achieve an emission reduction of 6.3% in the UK. Unlike the other mentioned studies, they did, however, assume vastly higher specific GHGE of the various food products. Not only agricultural emissions were taken into account, but also those from manufacturing, transport, packaging, storage, and supermarket operations (Kehlbacher et al., 2016). García-Muros et al. found that a carbon-based food tax of 50 EUR t^{-1} CO_2e could reduce food-related GHGE by 7.6% in Spain and diets became healthier as a side effect (García-Muros et al., 2017). Bonnet et al. found a GHGE reduction of 1.5% for a tax of 56 EUR t^{-1} CO_2e on various meat types in France. A tax level of 200 EUR could increase the reductions to 4.8%. A high tax on beef alone would already capture 53% of the mitigation potential (Bonnet et al., 2018). Janssen and Säll used the CAPRI model to simulate a GHGE tax on livestock products in the EU and found a reduction of agricultural GHGE of up to 4.9% for a tax level of 290 EUR t^{-1} CO_2e.

Most authors identify inelastic demand as the main reason for the moderate consumption shifts. The results are relatively similar with agricultural GHGE reductions between 4 and 10% for tax levels roughly between 50 and 60 EUR t^{-1} CO_2e. All authors do however assume a reduced production at reduced domestic demands, which is a vast overestimation.

The studies shown above examine taxes in a single country, in the EU or in one case globally. They simulate a consumption decline in these areas and conclude that a similar production and hence GHGE decline takes place. They omit the possibility of producers to increase exports to compensate for the reduced domestic demand. This trade adjustment would result in a “carbon leakage”, i.e. a GHGE increase caused by a given mitigation legislature outside the area of its legal force. In this study, we quantify this leakage and estimate how much exports would increase as a result of domestic demand reductions following a GHGE-based taxation of all agricultural products (livestock and plant-based). The consequential efficiency loss of the GHGE tax regarding GHG mitigation is also examined. The regional scope of this examination is the European Union (EU).

A GHGE-tax is a currently much-debated policy instrument and is propagated to reduce emissions and improve the sustainability of the economy. Our quantification helps policy makers and academics to increase their knowledge on the mechanics of such a tax to develop better policy instruments for more sustainability in agriculture. The basic findings can also be transferred to other regions and sectors.

2. Materials and methods

We use a modified version of the European Forest and Agricultural Sector Optimization Model (EUFASOM) to assess the complex adjustments of agricultural production systems and agricultural commodity markets in response to carbon prices (cf. Zech and Schneider, 2019). To examine the effects of the tax, we modified the model such that the tax revenue is subtracted from the economic surplus measured in the objective function. The tax revenue is calculated by multiplying the tax level with the tax base – the demand for the agricultural product times its average GHGE – and then summing over all products in all EU-countries. A simplified version of this complicated equation is given in Equ. 1. Maximizing the altered objective function leads to a new market equilibrium with a tax in place.

Equ. 1: Modified objective function

$$Surplus_{Tax} = Surplus - \sum_{r \in EU;p} \left[Demand_{r;p} specEM_p EmTax\right]$$

with	$Surplus_{Tax}$ (variable)	=	Total economic surplus with GHGE-tax in the EU in 1000 USD
	Surplus (variable)	=	Total economic surplus with no GHGE-tax in the EU in 1000 USD
	$Demand_{r;p}$ (variable)	=	Demand for product p in region r in 1000 t
	$specEM_p$ (parameter)	=	Specific agricultural GHGE of product p (EU-average) in t CO_2e t^{-1}
	EmTax (parameter)	=	Emission tax rate in USD $t^{-1}CO_2e$

The demand of GHGE-intense products is “punished” this way, as increased demand for them decreases the total economic welfare. It becomes more favorable to demand less of these products and increase the demand of less GHGE-intense alternatives. To prevent implausible reductions in commodity demand, regional food intakes are restricted to not fall below the reported levels of energy and protein intake.

We used EU-averages of the specific, agricultural GHGE of the various food commodities as the tax base. Emissions released from the use of energy on farms or during transportation, processing, packaging, retail, and refrigeration are omitted as they are beyond the scope of the used agricultural sector model and the available data are fragmentary. Table 1 depicts the assumed specific GHGE:

All simulations were carried out using EUFASOM - a bottom-up, dynamic partial equilibrium model covering all 28 countries in the EU and 18 rest-of-the-world regions. The model integrates physical and economic relationships. The physical relationships enforce correct mass and volume balances for primary and processed goods. In particular, the sum of all domestic and foreign product uses cannot exceed the sum of all domestic and foreign supply processes. The economic relationships in EUFASOM include an accounting of benefits and costs in the agricultural sector with endogenous commodity prices. The objective function maximizes total economic surplus consisting of consumption benefits and resource rents minus the costs of production, processing, and transportation summed over all regions, commodities, and resources. Product demand is depicted through downward-sloped functions with constant own-price elasticities. A model solution mimics the competitive market equilibrium by choosing agricultural production and processing activities such that economic surplus is maximized. Production covers 17 important crops (5 types of cereals, 4 types of oil crops, starchy roots, pulses, vegetables, fruits, and others), 4 types of meat (beef, mutton/goat, pig, poultry), sugar, and 5 plant oils (Rapeseed, soya, palm, other annual, other perennial). Crops are grown using four types of soil management (high input irrigated, high input rainfed, low input rainfed, minimal input rainfed). Five types of agricultural GHGE are modelled: methane (CH_4) from enteric fermentation in ruminant animals, CH_4 and nitrous dioxide (N_2O) from manure storage, N_2O from the application of manure and synthetic nitrogen fertilizer on cropland and pasture, and other emissions, e.g. from burning residues or cultivating rice. All GHGE are calculated in CO_2e.

Historical data on production, trade, product use, prices, and GHGE are used to calibrate the model to a reference and are mostly taken from the FAOSTAT database (FAO, 2015a, 2015b). All reference quantities and prices are averaged over the years 2007–2011 to reduce the impact of annual variations. Own-price elasticities of demand are taken from (Muhammad et al., 2011) and measure the change in commodity demand in response to a change in its price.

3. Agricultural GHG emissions in the EU

For our reference period from 2007 to 2011, we calculated that the EU's agriculture released about 412 Mt CO_2e per year. 56% of these emissions are directly attributable to livestock, i.e. they were generated during enteric fermentation in ruminants (162 Mt) and manure management (69 Mt). The remainder (182 Mt) was released in arable farming. As argued above, a large part of these emissions can also be attributed to livestock activities, since the majority of the produced crops, and practically all of the produced grass-based feeds, are fed to livestock. The specific GHG intensities shown in Table 1 are obtained by allocating these GHGE to the corresponding levels of livestock production.

Table 1
Average specific GHGE for various foods in the EU (rounded).

Food product	Specific GHGE [t CO_2e t^{-1}]	Cost increase at tax of 50 USD t^{-1} CO_2e [USD kg^{-1}]
Beef	12.6	0.63
Mutton/goat meat	12.2	0.61
Pig meat	4.1	0.21
Poultry meat	2.7	0.14
Poultry eggs	3.8	0.19
Milk	1.0	0.05
Cereals	0.2 (Corn) – 2.7 (Rice)	0.01–0.14
Pulses	0.0	0.00
Starchy roots	0.1	0.01
Nuts	0.1	0.01
Vegetables/fruits	0.0	0.00
Plant oils	0.3 (Rapeseed) – 1.0 (Soya)	0.02–0.05

The GHGE-balance of the EU's agriculture sector are implicitly be influenced by trade. Net-exports of GHG-intense products would implicitly lower the domestic GHGE-balance, as the emissions could be attributed to foreign consumption. Net-imports would have the opposite effect. During the reference period, 9.1 Mt of the very GHG-intense ruminant meats were annually produced in the EU while another 0.6 Mt were net-imported. However, for all types of meat combined, a total of 43.7 Mt was produced of which 1.4 Mt were net-exported. The overall GHGE-balance of meat-trade was hence almost neutral. Adding the GHGE of the 8.4 Mt of milk that are net-exported out of the 157.4 Mt produced, makes the EU a net-exporter of agricultural GHGE – yet only by a minimal percentage of all agricultural GHG that are emitted.

4. GHG tax and market dynamics of carbon leakage

When a GHGE tax is imposed on food products in the EU, international commodity markets will adjust and move to a new equilibrium with a lower consumption of GHG-intense products. This market adjustment is illustrated in Fig. 1. The tax burden would shift the demand function down ⓪ leading to a lower autarkic market equilibrium ①. Consequently, the excess supply function for the EU would also shift downwards leading to a new trade equilibrium with higher exports from the EU to the rest of the world ②. Simultaneously, the international market price would decrease ③. Domestic demand in the EU would decrease more ④ than supply ⑤ indicating a certain ineffectiveness of a regional GHGE tax.

Due to the tax, consumers in the EU would demand fewer GHG-intense products. However, EU producers would partially compensate the loss in domestic demand through higher exports. Hence, only a fraction of the reduced domestic demand is mirrored by a lowered production.

The desired effects of the tax are reduced GHGE through reduced demand for GHG-intense products. However, the actual GHGE reduction in the EU would correspond to the reduction in production ⑥. Depending on supply and demand elasticities, the realized emission reductions could be substantially lower than the demand based emission reductions ⑦.

The consumer demand function represents consumer preferences and does not change with a GHGE tax. However, the perceived consumer demand function by producers shifts downward leading to lower producer prices in the EU and lower prices for producers and consumers in the rest of the world. The price for EU consumers therefore increases ⑧, while that of EU producers falls. In addition, demand in the rest of the world would increase ⑨ due to lower prices. Production outside the EU would decrease ⑩ leading to further GHGE reductions ⑪. Note that Fig. 1 is not drawn to scale and only depicts qualitative market adjustments.

In summary, the tax would induce a demand shift from the EU to the rest of the world and a production shift in the reverse direction. Thus, the total emission reduction would include a direct and an indirect effect related to decreased production inside and outside of the EU. However, the total GHGE savings would be smaller than suggested by the demand reduction in the EU. The less than proportional decrease in emissions is the result of emission leakage.

5. Results and discussion

5.1. Change of demand, trade, and production

Our results quantify how production and consumption of GHGE-

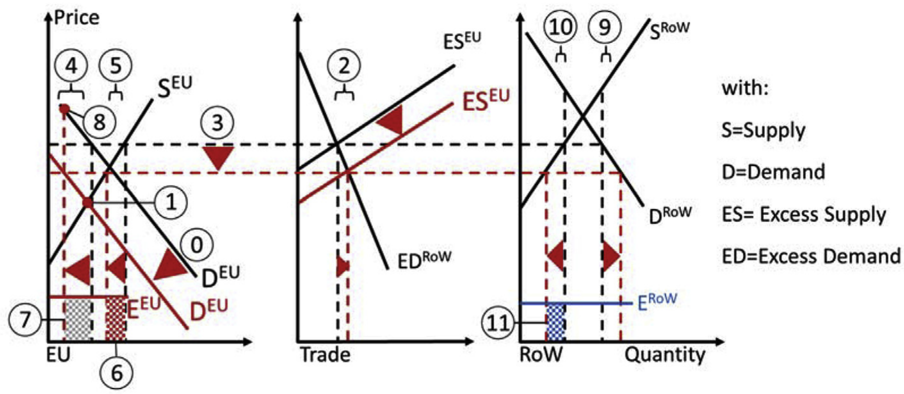

Fig. 1. Market dynamic of products taxed on a GHGE-basis.

intensive foods change as the tax increases. Because producers offset the loss in domestic demand through higher net-exports, the impact on production is considerably smaller than the impact on consumption. Fig. 2 exemplarily shows the aggregated results for all meat products combined in the EU, as they are the most GHG-intense foods.

Total meat consumption in the EU falls by about 2% at a tax level of 50 USD t^{-1} CO_2e. Relatively low demand elasticities are the most important reason for this rather small shift in consumption. For example, a tax of 50 USD t^{-1} CO_2e would increase the cost of beef by only 0.63 USD kg^{-1} and much less for all other products. This shift is not enough to obtain substantial reductions in consumption. Other authors also found low consumption reactions to emission taxes on food products. (Säll, 2018), for instance, simulated a tax on meat in Sweden and noticed only small changes in demand due to the low price elasticity. Further studies with similar results are discussed in the introduction.

On the other hand, EU meat exports increase by about 41%. Lower perceived demand in the EU leads to a price decrease in international markets making meat more affordable outside the EU. This means substantial leakage, because the increased net-exports offset 70% of the demand reduction. Thus, only 30% of the demand reduction translates into a reduction of production. In the rest of the world, demand for meat increases slightly by about 0.2% while its production declines by 0.1% at a tax level of 50 USD t^{-1} CO_2e in the EU.

Fig. 3 shows that the exports increase stronger for more GHGE-intense meat types at increasing tax rates. The exports of bovine, mutton/sheep, and pig meat rise relatively strongly compared to exports of poultry meat.

While the consumption of livestock products decreases slightly, other products are consumed in slightly larger amounts to maintain the calorie and protein intake. At a tax level of 50 USD t^{-1} CO_2e, the intake of cereals increases by 0.5%, that of pulses by 6.4%, and that of oil crops by 15%.

5.2. GHGE reduction and leakage

Agricultural GHGE decline as the GHGE tax on meat increases. If lowered consumption for these products would result in an equivalent reduction of GHGE – as assumed in the abovementioned studies – GHGE would decrease by about 1.92% or ca. 7852 kt CO_2e at a tax of 50 USD t^{-1}. Such emission reductions would be fairly consistent with previous estimates if the same specific emission coefficients are employed. Some previous studies use much higher specific GHGE for beef, pork, and other products because they also include emissions from transportation, packaging, retail, and refrigeration. Unlike previous studies, we enforce per-capita intakes of both energy and protein to not fall below observed levels. These restrictions prevent symmetric demand reduction across different livestock products. Most previous studies only enforce a lower bound on per-capita calorie intake.

The overall emission reduction estimates of our model are substantially smaller than the reduction in consumption. At a tax level of 50 USD t^{-1} CO_2e, agricultural GHGE would decrease in the EU only by 0.41% (1670 kt CO_2e) instead of 1.92% due to increased net-exports. Decreased meat production outside the EU, however, would reduce this emission leakage and yield additional GHGE reductions equivalent to 0.68% of the EU's agricultural GHGE or 2800 kt CO_2e. Combining adjustments of EU and non-EU producers, we still estimate an overall leakage effect of about 43%. Thus, only

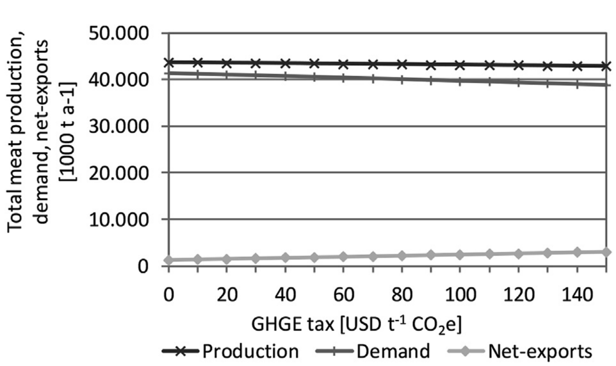

Fig. 2. Impact of GHGE tax on EU meat sales on production, consumption, and net exports of meat.

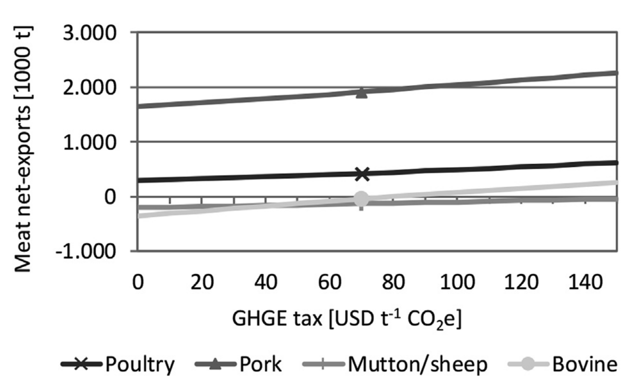

Fig. 3. Change of net-exports of meat types dependent on GHGE tax in the EU.

about 57% of the potential GHG mitigation induced by the demand reduction for GHG-intense foods would be realized. However, an absolute, global GHG mitigation potential of ca. 4465 kt CO_2e is calculated for a tax level of 50 USD t^{-1} CO_2e. GHGE reduction and leakage effects remain in similar proportions for varying tax levels.

6. Conclusion

Our study shows that a GHGE tax on food products may be less effective than suggested by previous studies. Not even their relatively low predictions for GHGE reduction seem realistic, if the tax is only introduced regionally and trade is not further restricted. Increased net-exports of GHGE-intense meat products would offset 70% of the achieved demand reduction. A slight production shift moderates this effect, as non-EU regions would produce less meat in that case. Total GHGE leakage, however, still lies around 43%.

Policy makers can use our theoretical results to improve the practical effects of sustainability policies. Leakage should be considered when designing climate policies, especially when these policies have a limited regional scope.

There are two principle remedies to prevent adverse leakage effects. The first remedy would be to increase the scope of the climate policy to global coverage. If such an expansion is politically infeasible, regulating countries, e.g. the EU, could implement trade restrictions. Trade restrictions, while not very popular, are justified by economic theory for environmental policies of limited scope. These trade restrictions could be implement as export quotas or as export tariffs.

Our study bases the tax burden on the average emission level for different products. A more efficient regulation would be to use a more specific tax which differs across different production technologies. Such a policy would provide an incentive to produce the same livestock commodity in an emission-friendlier way. However, such a policy would require a very detailed monitoring of production chains and associated producer decisions. It might further violate international trade rules.

Dietary changes, especially in countries with high meat consumption, could be another way to reduce the production of these GHGE-intense products. Such changes might be based on a desire for healthier nutrition with less livestock-based foods. It would, however, be necessary that countries with currently low meat consumption do not increase their demand, as many of them did in recent years.

Declarations of interest

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