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Environmental impacts of household food consumption and the efficiency of a carbon tax

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MASTER THESIS

for

Student Renate Stakvik

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Environmental impacts of household food consumption and the efficiency of a carbon tax
Miljøeffekter av husholdningers kosthold og virkninger av en karbonskatt

Background and objective

The AFOLU sector represents a quarter of the global anthropogenic GHG emissions and is one of the key growth sectors in the future. Food consumption is an important source of these emissions, and by transitioning consumer diets to be less emissions intensive, a reduction in GHG emissions from the agricultural sector could be achieved. This study will look into the possible reduction of global GHG emissions due to an implementation of a tax on certain agricultural food products. It will also look into the consumer responses due to increased prices in food products following a tax implementation. The analysis will be done within an EEMRIO framework.

The following tasks are to be considered:

1. Perform a review of the relevant literature
2. Perform an assessment of food related GHG footprint, providing a country-level comparison, and an investigation on domestic versus foreign sources.
3. Develop scenarios for different applications of carbon-tax instruments.
4. Analyze the effects of a carbon tax on the prices of consumer goods
5. Analyze the consumer responses to the change in prices of agricultural food products
6. Analyze total effects on global GHG emissions
7. Analyze and discuss the results

Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to “Regulations concerning the supplementary provisions to the technology study program/Master of Science” at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student’s name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)

☐ Field work

Department of Energy and Process Engineering, 15. January 2018

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Richard Wood

Academic Supervisor

Research Advisor: Johannes Többen

Abstract

The agriculture, forest and other land use (AFOLU) sector is responsible for roughly one quarter of the anthropogenic global GHG emissions. Agriculture is the main driver in the AFOLU sector, as agricultural products such as food, biofuels and raw materials drive both deforestation and other land use change. Food is by far the main driver of the agricultural products, and is therefore a key target for mitigation measures. A carbon tax is a policy instrument that can be used to mitigate carbon footprints (CFs) by increasing costs that consequently lead to changes in demand. In this thesis, a supply tax of 100€/tCO_2-eq is added to the meat and dairy industries in the EU, Switzerland and Norway, with the aim of mitigating GHG emissions from the AFOLU sector. By adding a tax on the suppliers, both the supply- and the demand side are targeted, as it is anticipated that the producers will fully pass on the increase in cost, resulting in higher prices in the grocery store. A revenue neutral tax is assumed, as the tax revenue goes to lowering income taxes, generating a so-called double dividend. A multi-regional input-output (MRIO) analysis is used to find the mitigation potential of a such a tax by modelling the change in carbon footprint related to the changes in demand following price increases, using both price and income elasticities. Contrary to similar studies, this analysis also considers the rebound effects from a changed diet cost and that of changes in income from the recycled tax revenue. A reduction of 2% on average, relative to the total household footprint from the EU, Switzerland and Norway was obtained. The supply tax also generated a positive effect on both employment and value added of 0.4% and 0.7% respectively.

Sammendrag

AFOLU- (land-, skog og andre arealbruk) sektoren står for omtrent en fjerdedel av de globale menneskeskapte klimagassutslippene. Landbruk er den største driveren innen AFOLU-sektoren, da landbruksprodukter som mat, biodrivstoff og råmaterialer driver både nedhogging av skog og etterspørsel etter flere områder å produsere på. Mat er det landbruksproduktet som skaper størst etterspørsel, og er derfor et nøkkelområde med tanke på tiltak for å redusere klimagassutslipp. En karbonskatt kan bidra til reduksjon av utslipp fra AFOLU-sektoren ved å øke kostnadene på landbruksprodukter som igjen fører til endring i forbruk. I denne oppgaven tillegges en skatt på 100€/tCO_2-ekvivalenter på kjøtt- og meieriprodusentene i EU, Norge og Sveits, med et mål om å redusere klimagassutslipp fra AFOLU-sektoren. Ved å tillegge en skatt på produsentene vil både produsentene og forbrukerne bli berørt, siden den økte kostnaden trolig vil bli videreført helt eller delvis til forbrukerne, som da resulterer i økte priser i butikkene. I denne oppgaven er skatten antatt å være inntektsnøytral for myndighetene, siden skatteinntektene brukes til å redusere forbrukernes inntektskatt, og med det genereres et såkalt dobbelt utbytte (double dividend). En multiregional input-output (MRIO) analyse brukes til å finne reduksjonspotensialet knyttet til endring i forbruk som følger av karbonskatten, ved bruk av både priselastisitet og inntektselastisiteter. I motsetning til lignende studier, tar denne oppgaven for seg tilbakeslagseffekter (rebound effects) som følge av endringer i kostnad av diett og endringer i inntekt grunnet de reduserte skatteinntektene til forbrukerne. Via skattepåleggelsen ble en gjennomsnittlig reduksjon på 2% oppnådd, relativt til totalt fotavtrykk for husholdninger i EU, Norge og Sveits. Skatten tillagt produsentsiden hadde også en positiv innvirkning på både ansettelse og verdiskapning på henholdsvis 0.4% og 0.7%.

Preface

This thesis is the finalizing work of the two-year master program of Industrial Ecology at the department of Energy and Process Engineering at NTNU. I would like to extend my sincere gratitude to my supervisor prof. Richard Wood and my co-supervisor Johannes R. Többen for your skillful guidance and patience throughout the semester. Your help has been a great support for me when writing this thesis. I would also like to extend my thanks to Kjartan Steen-Olsen, who was one of my co-supervisors for the project thesis, that led to this work. And finally, a special thanks to Ana María and the rest of my fellow students, for your company, advice and support.

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List of acronyms

AFOLU	Agriculture, Forestry and other Land Use change
CF	Carbon Footprint
CO_2-eq	Carbon dioxide equivalents
EUR	Euros
FD	Final Demand
GHG	Greenhouse gas
IOA	Input output analysis
IPCC	Intergovernmental Panel on Climate Change
kt	kilo tons
LCA	Life Cycle Assessment
MEUR	Million euros
MRIO	Multi-Regional Input Output
Mt	Mega tons
nec	Not elsewhere classified
N-fertilizer	Nitrogen fertilizer
tCO_2-eq	Tons Carbon dioxide equivalents
VA	Value added

Introduction

The agriculture, forest and other land use change (AFOLU) sector represents about one quarter of the global anthropogenic GHG emissions (IPCC, 2014). Both deforestation and other land use changes are driven by the demand for agricultural products, such as food, biofuel and raw materials, which makes agriculture a key target when it comes to mitigation measures (Carus and Dammer, 2013). Despite biofuel's and raw material's increasing importance, food production is still by far the most important driver (Carus and Dammer, 2013). The emissions related to food production is emitted on the supply side, and the main focus has therefore been on efficiency measures there. However, it is mostly private households who drive the demand for food (Creutzig et al., 2018; Hertwich and Peters, 2009), and the mitigation potential is thus large in lifestyle changes and reduction of demand (Creutzig et al., 2018). Policy instruments that are implemented with the aim of reducing the impacts from agriculture should optimally target both the supply side and the demand side, as this could potentially open up for larger reductions.

In general, there are two different policy instruments suitable for reducing environmental impact from agriculture production (Stern Review, 2007). One approach, command and control, involves either a reward or punishment for staying below or exceeding a certain emission cap, however, this approach is not commonly used in the literature regarding mitigations from agriculture production. The other approach is carbon pricing, where one could either implement a certain carbon tax based on the emissions (directly or indirectly), or a tax based on the social cost of emission. Alternatively, the cap-and-trade approach is a combination of the two methods mentioned above (Stern Review, 2007). This comprises a certain carbon cap but allows for quota trading, which means that if someone is exceeding the emission cap, they can buy emission quota from someone that lies below the emission cap. An example of this is the EU's emission trading scheme, where a uniform carbon price is added on the GHG emissions from specific heavy industry activities, such as energy generation and metal production (Stern Review, 2007).

In this thesis, a "Pigouvian tax" is the policy instrument that will be used as a tool to reduce GHG emissions from the agriculture sector. A Pigouvian tax is a tax that targets market activities that leads to externalities, where the total cost is not included in the price of the final good/service (Stern Review, 2007). A Pigouvian tax can thus be used to internalize the externality agriculture emissions inflict on the society, due to the environmental impact from the production that is not reflected in the prices of food (Stern Review, 2007). Pigouvian taxes also tends to be favored by economists over regulatory measures, as they can provide a *double dividend* (Goulder, 2013), e.g. where one sector benefits of reduced emissions and another sector benefits from lower taxes by the use of the tax revenue.

There are several ways a Pigouvian tax could be introduced on the market. The tax could be added either to the demand side or to the supply side. A tax directly on the emissions is theoretically preferable as it covers the actual damage (Garnett, 2012), however, a tax directly on emissions is only preferable if the emissions are relatively easy to monitor, such as point emissions (Schmutzler and Goulder, 1997). As most of the emissions coming from the agriculture sector are not point emissions, such as methane from enteric fermentation and nitrous oxide from fertilizers, a tax directly on the emissions as they occur, would require accurate monitoring on the farm level, and consequently lead to large monitoring costs (Wirsenius et al., 2011). Wirsenius et al. further state that the reduction potential is low on the supply side and therefore promote a tax on the demand side, as substitution of food products has a higher mitigation potential than efficiency measures on the supply side. To the authors knowledge, there has not yet been implemented a demand tax on agriculture products with the aim of reducing environmental impact, and the closest empirical evidence of a demand tax is that of saturated fat in Denmark, which had the aim of improving public health, but were withdrawn shortly after implementation (Jensen and Smed, 2013). However, there are examples in literature where a demand tax has been modelled (Abadie et al., 2016; Edjabou and Smed, 2013; Säll and Gren, 2015; Wirsenius et al., 2011), but there is a lack of literature targeting both suppliers and consumers with a demand tax.

Contrary to a demand tax, a supply tax gives the producers direct incentive to be more efficient. It could also urge consumers to be more attentive to what they consume if the increase in cost is passed on in parts or fully to them by the suppliers. In addition, adding a fair tax rate on the final good/service could be challenging (Edjabou and Smed, 2013). As Edjabou and Smed (2013) state, a tax on the emissions occurring in the supply chain will most likely end up at the consumer in the long run, as the producers are forced to either lower their emissions or pass the costs on to the consumer, and how much of the cost the producer can pass on depends on the competition in the market (Edjabou and Smed, 2013). However, a supply tax could lead to a carbon leakage, as it gives an incentive to rather import from countries without taxes to maintain the initial demand in each country. This gives motivation to tax larger areas such as the entire EU (Garnett, 2012), nonetheless, imports from non-EU countries still have to be considered, and this would have to be regulated with for instance tariffs. There is a lack of empirical evidence, as well as literature, of supply taxes that targets both the supply and the demand. There are, however, some examples of countries that have implemented a supply tax on inputs, such as Austria, Denmark, The Netherlands, Sweden and Norway, that have implemented a tax on nitrogen fertilizers, with varying mitigation success (Söderholm and Christiernsson, 2008).

When analyzing the mitigation potential of a carbon tax, the consumer response to price increases is a central aspect, as the resulting changes in demand is directly linked to how large the mitigations following a tax implementation will be. There are various ways of modelling consumer behavior, and the most common method is the use of price elasticities, which is defined as the percentage change in final demand (quantity) due to a percentage change in price. There are two types of price elasticities (Varian, 2010), own elasticities which consider the elasticity of a single good/service, and cross elasticities which are interrelated elasticities. For a normal good, the own price elasticity is normally negative, if it is above 1 in absolute terms it is considered elastic, and below 1 in absolute terms, inelastic. The cross price elasticities are positive if the good/service is a substitute (Varian, 2010).

In order to analyze the effects of a Pigouvian tax, it is necessary to establish a current environmental impact from the AFOLU sector, to facilitate a comparison, and this can be done using data from multiple regions in a so called multi-regional input-output (MRIO) analysis, which includes trade between nations (Tukker et al., 2013; Wood et al., 2014). With this method, a carbon footprint (CF) can be calculated, which quantifies the life cycle impacts embodied in consumption of goods and services. However, as MRIO in general are often used with aggregated data due to a top down approach, there could be a lack of detail making it less fit for policy decisions (Steen-Olsen et al., 2016).

The norm in the literature is a demand tax rather than a supply tax (Abadie et al., 2016; Edjabou and Smed, 2013; Wirsenius et al., 2011), and there is a lack of studies that targets both the supply side and the demand side. This study challenges that norm by investigating if a supply tax on meat and dairy industries will have a mitigating effect on the GHG emissions related to the AFOLU sector. Such a supply tax targets both the supply side and the demand side, as the supply side have the option of either reducing emissions from the production, or pass on the increase in cost to the consumers. In turn this leads to higher prices in the grocery store and subsequently nudges the consumers to choose less emission intensive food products. Contrary to similar studies, it also analyzes the rebound effects caused by changes in diet cost and changes in income from lowering income taxes.

The structure of the remaining thesis is as follows; “Model and data” describes the model setup, followed by “Results” that describes the results obtained, in “Discussion” the results are discussed, and finally “Conclusion and future work” concludes the work, in addition to giving a suggestion of future work.

Model and data

A demand driven input output (IO) model is used to analyze the effects of a supply tax on meat and dairy industries in the European Union plus Switzerland and Norway. The IO framework used in this thesis is based on the theory of (Miller and Blair, 2009) and of previous unpublished work of the author (Stakvik et al., n.d). Table 1 shows a simplified setup of an IOA table, where the inter-industry matrix **Z** (industries x industries), shows the flows in the economy from each of the producing industries (rows) to each of the consuming industries (columns). The value added vector, **v'** (1 x value added), is the value added to the industries containing information about labor, depreciation of capital, indirect taxes and imports. The final demand vector, **y** (industries x 1), contains information of consumption from households and governments, gross private domestic investments and net exports. The total output vector, **x** (industries x 1), shows the total output needed to fulfill a final demand **y**.

Table 1: Basic simplified IOA table (Miller and Blair, 2009)

	Industries (producers as consumers)	**Final Demand**	**Total Output**
Industries (producers)	**Z**	**y**	**x**
Value Added	**v'**		
Total input	**x**		

From Table 1, it is possible to derive the carbon footprint that will be the base of the method used in this thesis. The inter industry matrix **Z** consist of the **A**-matrix (industry x industry) which is a requirement matrix that contains information of the intra-industry requirements to produce one unit of output, and the diagonalized output vector **x**, indicated in equation (1):

$$\mathbf{Z} = \mathbf{A}\hat{\mathbf{x}} \tag{1}$$

The total output vector **x**, can be written as in equation (2):

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \tag{2}$$

Where **I** (industries x industries) is the identity matrix and **y** is the final demand. This can also be written as in equation (3):

$$\mathbf{x} = \mathbf{Ly} \tag{3}$$

Leontief inverse **L** (industries x industries) shows the total requirements needed to produce one unit final demand **y** and is defined as in equation (4):

$$\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1} \tag{4}$$

The last step to reach the footprint is by introducing the direct impact coefficients $\mathbf{S_{kj}}$ (stressor(s) x industries), where k is the type of pollutant per unit output of industry j. This shows the pollution impacts related to industry activity, and by multiplying this with the total output **x**, the environmental impact **F** (impact x industries), can be defined as in equation (5). If the type of pollutant is CO_2-eq (GHG), we then have the CF. The full derivation of the quantity model and environmental impact can be found in Appendix A.

$$\mathbf{F} = \mathbf{SLy} \tag{5}$$

With the CF established, we now have the base to analyze the effects of a supply tax. The analysis of the mitigation potential of the tax comprises the use of several models, such as the environmental quantity model that delivers change in environmental impacts due to a change in one or several of the inputs; emission intensities **s**, Leontief inverse **L**, and the final demand **y**, while the prices are held constant. The price model that gives the change in the price of output when a price on input is altered, while the quantities are held constant. And finally a demand model, where the response of changes in prices or changes in income are modelled by the use of elasticities. Figure 1 illustrates the interrelation of the different models, and the use of each model will be described in more detail below.

First, we analyze the effects of both demand side tax and supply side tax on consumer prices. The supply tax is assumed to be passed on in its full to the consumers, and the consumers' budget is assumed to be fixed (the sum of final demand is fixed). An exogenous cost is added to the VA, and through the price model the changes in cost of the final products are analyzed. For the demand tax, an exogenous cost is added based on the original food CF. The relative change in cost is assumed to be not higher than 60% to set a limit for the price increase, for both the supply and the demand tax. Second, the impacts of price changes on consumer behavior are analyzed. The price elasticities that are used to analyze the behavior comes from the study of Edjabou and Smed, (2013) due to the lack of literature including price elasticities (own and cross) for all the EU, thus the assumption is that EU, Switzerland and Norway have the same price response as Denmark, see the section of “Data and limitations”. A minimum of 10% use of original demand is assumed to avoid an unrealistic outcome where the demand reduces with over 100%. Third, the rebound effects due to changes in income following altered diet costs, and extra available money due to lower income taxes funded by the tax revenue. Finally, the carbon tax rate is described, as well as the use of data and the related limitations.

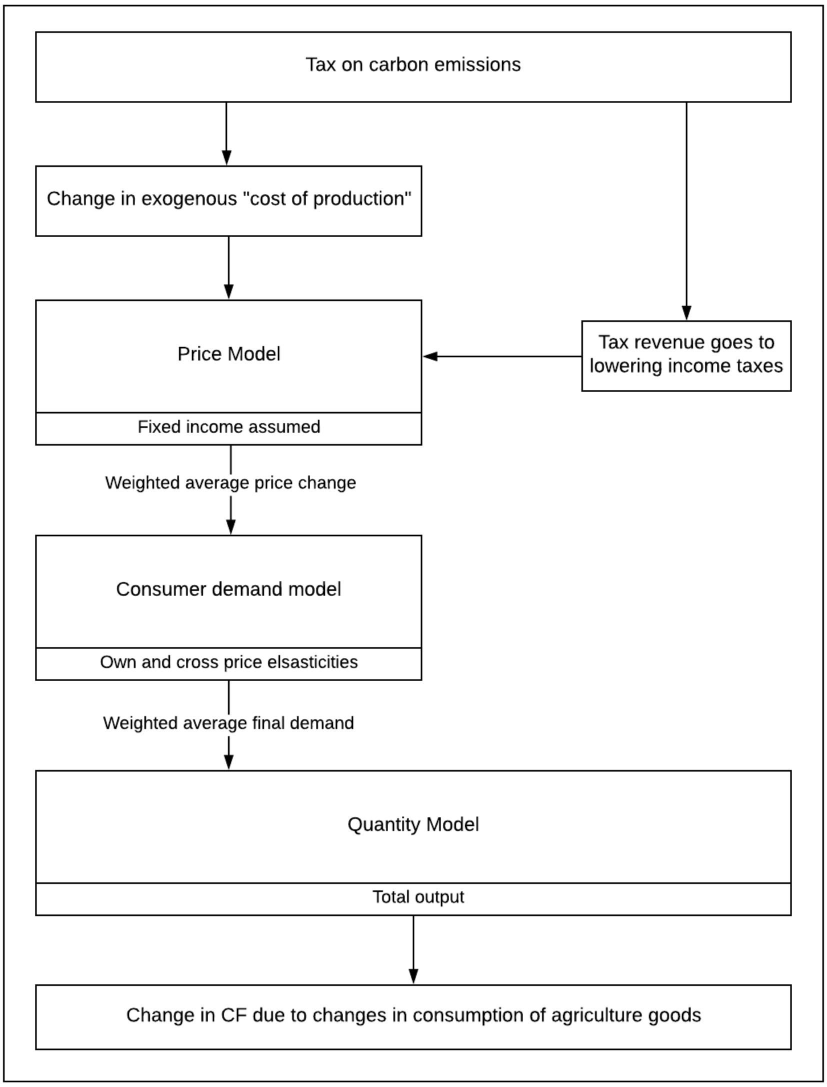

Figure 1: The model setup, illustrating the use of different models to analyse the effects of a carbon tax

Effects of demand side and supply side taxes on consumer prices

The starting point is finding the baseline household CF related to food consumption, which is derived from equation (5), but adapted to only include the impacts from the household demand given in equation (6), where $\mathbf{y_{hh,food}}$, is the food demand of households.

$$\mathbf{F_{CO_{2-eq,food}}} = \mathbf{s} * \mathbf{L} * \mathbf{y_{hh,food}} \tag{6}$$

In the case of demand tax, a CF is calculated with an emission intensity vector **s**, that only includes the intensities (CO_2-eq/output) of raw and processed meat and dairy products. By only looking at the emissions coming from the agriculture sector and not all emissions embodied in the consumption of these products, e.g. transport and factory emissions, the demand tax is more comparable to a supply tax. A tax of 100 €/tCO_2-eq is then multiplied with the CF footprint related to meat and dairy products and not only the raw industries that are taxed in a supply tax, as the consumers mainly demands processed food. This results in the absolute increase in price $\mathbf{p_{abs}}$, which is further divided on the total household demand $\boldsymbol{y_{hh}}$, to find the weighted average price changes $\Delta\mathbf{p}_{\mathbf{wa}_i}$ (food industries x 1) for each industry *i*, as given in equation (7):

$$\Delta\mathbf{p}_{\mathbf{wa}_i} = \frac{\mathbf{p_{abs}}}{\boldsymbol{y_{hh}}} \tag{7}$$

In the case of a supply tax the first step for the tax implementation is made using the price model. It is assumed that the industries fully pass on the increase in the cost of production (from the tax) to the consumers, in the form of higher prices on the final products in the grocery stores. An exogenous costs of production is thus added to the value added vector for all meat and dairy industries, and this results in a relative change in price of the final products, given by equation (8):

$$\tilde{\mathbf{p}} = (\mathbf{I} - \mathbf{A}')^{-1}\mathbf{v_c} = \mathbf{L}'\mathbf{v_c} \tag{8}$$

Where $\tilde{\mathbf{p}}$ (price x 1) is the price vector, **I** (industries x industries) is the identity matrix, **A** (industries x industries) is the direct requirement matrix indicating requirements per unit output, **L** (industries x industries) is the Leontief inverse matrix indicating the requirement per unit final demand, and finally $\mathbf{v_c}$ (1 x value added) is value added divided on the diagonalized output,

x (1 x output). The full derivation of the price model can be found in Appendix B. The weighted average price change $\widetilde{\mathbf{p}}_{\mathbf{wa}i}$, is found by multiplying import shares with the relative price change, $\widetilde{\mathbf{p}}$, as given in equation (9):

$$\widetilde{\mathbf{p}}_{\mathbf{wa}i} = \widetilde{\mathbf{p}} * \frac{y_{import}}{y_{hh}} \tag{9}$$

The import shares are included to only look at the price changes of the consumption of meat and dairy produced in the EU plus Switzerland and Norway. The beef imported from South America for instance, is not taxed in the case of a supply tax.

Impacts of price change on consumer behavior (own and cross price elasticities)

The changes in demand following changes in price can be found by the use of price elasticities, which is defined as the percentage change in quantity per one percent change in price, given in in equation (10):

$$\boldsymbol{\epsilon}_{\mathbf{p}ij} = \frac{\Delta\mathbf{q}/\mathbf{q}}{\Delta\mathbf{p}/\mathbf{p}} \tag{10}$$

Where $\Delta\mathbf{q}/\mathbf{q}$ is the percentage change in quantity, $\Delta\mathbf{p}/\mathbf{p}$ is the percentage change in price, and $\boldsymbol{\epsilon}_{\mathbf{p}ij}$ (food industries x food industries) is price elasticities for each industry i and each cross price elasticity for each industry j. The own price elasticities are generally negative for a normal good, indicating that if the price of a good increases, the demand for it goes down. The cross elasticities are positive if they are a substitute for the good, e.g. the demand for vegetables goes up when the demand for beef goes down following a price increase, and negative if they are closely related, e.g. if the demand for burgers goes down following a price increase, the demand of burger bread also goes down. By multiplying the weighted average price change $\Delta\mathbf{p}_{\mathbf{wa}_i}$ with the price elasticities for food $\boldsymbol{\epsilon}_{\mathbf{p}ij}$, we transit from the price model to the quantity model. This results in the relative change of demand $\Delta\mathbf{y}_j$ (industries x 1) for industries j given in equation (11):

$$\Delta\mathbf{y_j} = \Delta\mathbf{p}_{\mathbf{wa}_i} * \boldsymbol{\epsilon}_{\mathbf{p}ij} \tag{11}$$

From the relative change in final demand $\Delta\mathbf{y_j}$, the absolute change in FD $\Delta\mathbf{y_{j,abs}}$, can be found by multiplying the relative change $\Delta\mathbf{y_j}$ with the original household demand. The weighted average FD $\Delta\mathbf{y_{wa\mathit{i}}}$, can be found by multiplying it with the import shares, as given in equation (12):

$$\Delta\mathbf{y_{wa\mathit{i}}} = \Delta\mathbf{y_{j,abs}} * \frac{y_{import}}{y_{hh}} \tag{12}$$

The related change in CF due to the change in demand following a tax $\Delta\mathbf{F_{CO_2-eq,tax}}$, can be found by inserting the weighted average final demand $\Delta\mathbf{y_{wa\mathit{i}}}$ in equation (6).

Rebound effects due to income changes

The changes in the CF due to shifts in diets are derived, and one approach could be to only consider the changes in CF due to the consumer responses to price change, but this thesis is going to take it a step further and looking at the rebound effects from changes in the budget (income). For that, income elasticities will be used, defined as the percentage change in demand per percentage change in income, as given in equation (13):

$$\boldsymbol{\epsilon}_{\mathbf{i}i} = \frac{\Delta\mathbf{q}/\mathbf{q}}{\Delta\mathbf{i}/\mathbf{i}} \tag{13}$$

Where $\Delta\mathbf{q}/\mathbf{q}$, is the percentage change in quantity (or demand) and $\Delta\mathbf{i}/\mathbf{i}$, is the percentage change in income, and $\boldsymbol{\epsilon}_{\mathbf{i}i}$ is the income elasticities for each industry *i*. Due to the price changes on meat and dairy, there will be a shift in the demand modelled by price elasticities, as explained earlier. Consequently, the diets will either be costlier or less costly depending on how the consumer responds to the increased prices. If the diets are costlier, the consumers have to reduce the consumption of other products, and since the budget is assumed to be fixed (sum of FD is fixed) there will be a decrease in the total CF. If the diets are less costly, the consumers will have more available money to spend, and will buy something else that also has a CF, leading to a so-called rebound effect where total reductions are lower total than expected, due to the spending of the extra available money. The percentage change in income due to more/less costly diets is calculated, as given in equation (14):

$$\Delta\mathbf{i}/\mathbf{i} = \frac{-\Delta\mathbf{y}_{\mathbf{wa}j}}{\mathbf{y}_{\mathbf{hh}}} \tag{14}$$

Where the percentage change in income $\Delta\mathbf{i}/\mathbf{i}$, is found by dividing the weighted average change in demand $\Delta\mathbf{y}_{\mathbf{wa}j}$, on the baseline household FD, $\mathbf{y}_{\mathbf{hh}}$, resulting in a relative change in income due to changed diet costs. The sign in front of the weighted average change in demand $\Delta\mathbf{y}_{\mathbf{wa}j}$ is negative because if the sum of the diets cost is less than before (negative), this will now be positive income available to be spent on something else. The percentage change in income $\Delta\mathbf{i}/\mathbf{i}$, is then multiplied with the income elasticities $\boldsymbol{\epsilon}_{\mathbf{i}i}$ for each industry *i,* to find the percentage change in demand $\Delta\mathbf{y}_{FD1}$, as given in equation (15). Thereafter, this is multiplied elementwise with the household FD to get the absolute change in demand due to altered costs of diets, $\Delta\mathbf{y}_{FD1,abs}$.

$$\Delta\mathbf{y}_{FD1} = \Delta\mathbf{i}/\mathbf{i} * \boldsymbol{\epsilon}_{\mathbf{i}i} \tag{15}$$

From the increased prices on meat and dairy following a tax, the government will receive a tax revenue. The tax is however, assumed to be revenue neutral to the government budget and is recycled back to the consumers in the form of lower income taxes. However, since the consumers now have "extra" money to spend, they will spend it on goods and services that also have a CF, and this will automatically lead to an increase in the total CF. The percentage change in income due to the lowered income taxes is given in equation (16):

$$\Delta\mathbf{i}/\mathbf{i} = \frac{\mathbf{T}}{y_{hh}} \tag{16}$$

Where the tax revenue **T**, in each country is divided on the baseline household FD in each country resulting in a percentage change in demand for each country. The percentage change in final demand due to the reduced income tax $\Delta\mathbf{y}_{FD2}$ is found by multiplying the percentage change in income $\Delta\mathbf{i}/\mathbf{i}$,with the income elasticities $\boldsymbol{\epsilon}_{\mathbf{i}i}$, given in equation (17):

$$\Delta\mathbf{y}_{FD2} = \Delta\mathbf{i}/\mathbf{i} * \boldsymbol{\epsilon}_{\mathbf{i}i} \tag{17}$$

The absolute change in final demand due to the recycled tax revenue $\Delta\mathbf{y}_{FD2,abs}$, is found by multiplying the percentage change in FD $\Delta\mathbf{y}_{FD2}$, with the baseline household demand. The absolute changes in demand $\Delta\mathbf{y}_{FD1,abs}$ and $\Delta\mathbf{y}_{FD2,abs}$ are then inserted in equation (6), to find the CF related to these. Equation (18) illustrates the different sections of the CF after the tax implementation on meat and dairy.

$$\mathbf{F}_{CO_2-eq,new} = \mathbf{F}_{Baseline} + \Delta\mathbf{F}_{\mathrm{CO_2}-eq,tax} + \Delta\mathbf{F}_{\mathrm{CO_2}-eq,FD1} + \Delta\mathbf{F}_{\mathrm{CO_2}-eq,FD2} \tag{18}$$

The change in CF due to price changes $\Delta\mathrm{F}_{\mathrm{CO_2}-eq,tax}$, is added to the baseline household CF, $F_{Baseline}$. The resulting sum of this will be a lower CF than the baseline CF, however, some industries will show a decrease (e.g. cattle), while others an increase (e.g. plant based food). Then, the CF related due to costlier or less costly diets $\Delta\mathrm{F}_{\mathrm{CO_2}-eq,FD1}$, is added, and here are both positive and negative values. Finally, the CF due to the recycled tax revenue $\Delta\mathrm{F}_{\mathrm{CO_2}-eq,FD2}$ is added, which will give an increase in the total CF.

Carbon tax

Choosing an effective but at the same time fair carbon tax rate is not an easy task, as it should be set high enough to match the social costs of emission (Stern Review, 2007), yet not too high in order to have a functioning economic market of the taxed industries. The goal of the carbon tax is to reduce emissions from the production of agriculture goods by reducing the consumption of high intensive food products, but not to halt the production and consumption entirely. The Stern Review (2007) suggests a tax rate of 85US$ per ton of CO_2-eq, which equals to roughly 58 € per ton of CO_2-eq. This suggestion was given in 2007, and could be regarded by some as an outdated value. A value suggested by van den Bergh and Botzen (2014) of US$125per ton of CO_2-eq, which equals to just above 100€ per tCO_2-eq, will be used instead. In their paper, they state that this value is in the lower bound of what they found in literature, and that is "conservative and realistic". However, to the authors knowledge, there has not yet been a large scale implementation of a carbon tax with the intention of reducing emissions from the agriculture sector, and that makes it difficult to predict the most effective rate.

Data and limitations

In this thesis, the environmentally extended input-output database EXIOBASE version 3.4 was used for all calculations (Wood et al., 2014). Several models were used, including the quantity model, the price model and a demand model, see Figure 1. The baseline carbon footprint was calculated using the quantity model (Appendix A) and the tax implementation model was calculated using both the quantity model and the price model (Appendix B), in addition to the use of price and income elasticities to model the consumer behavior. The own and cross price elasticities derives from a study of Edjabou and Smed (2013), and were adjusted to match the aggregation level of EXIOBASE. The price elasticities, as well as a correspondence matrix, can be found in Appendix C. Finally, the income elasticities that were used to model the change in behavior due to a change in income, from both diet cost changes and reduced income taxes, derives from a study by Tisserant et al. (In preparation).

The results displayed in this thesis are heavily dependent on the price elasticities that are used, especially as the assumption is that all of the countries in focus have the same price response as Denmark, which is an important source of error. The study of Seale et al. (2003) for instance, includes own price elasticities for 114 countries for three different income levels, but they exclude the cross price elasticities, which are important to analyse the consumer response to a change in price. Due to a lack of literature on own and cross price elasticities, it was therefore decided to use the price elasticities from Edjabou and Smed (2013), although the author acknowledges that this is a bold assumption.

Another limitation for the price changes are related to the exogenous cost added to the value added (VA) vector in EXIOBASE, as the VA already includes taxes less subsidies on the different products purchased. Thus, when adding an exogenous cost on the meat and dairy industries in all of EU, Switzerland and Norway, the relative changes in price could be much higher for the countries that initially have low taxes on food. Many of the countries in focus have subsidies on meat and dairy, and this is not considered in the modelling in this thesis. The relatively high price changes that occurs could be a consequence of some countries subsidizing food industries and others not, and it was assumed that a cap of 60% increase in price would "cut off" the highest price changes, which were also assumed to be unrealistic.

Results

This section first illustrates the baseline impacts from the household food demand for the EU, Switzerland and Norway, comparing the impacts from food consumption and food production. Thereafter, the effects on the CF of adding a supply tax on meat and dairy industries are illustrated in addition to other effects following the tax implementation.

Baseline footprints

To analyze the effects of the carbon tax, the environmental impact from the baseline household food demand for the EU is calculated, given in Figure 2. The figure is divided in four showing; a) the consumption based emissions, b) the production based emissions, c) the consumption based emissions per capita and d) the production based emissions per capita. From Figure 2a, the emissions from household consumption is highest in central and western Europe plus Italy, which makes sense as they are all large economies in the EU. However, looking at the production based emissions in Figure 2b, the impact is lower for the same countries, apart from France, which has the same emission level for both cases. This indicates that the carbon intensity of the food consumption in central Europe, western Europe and Italy is higher than the carbon intensity of the food they produce. This could subsequently be related to the type of imported food they consume versus the type of food they consume originated domestically, and the emission intensity per output for food across countries.

Looking at the ranking of countries in Figure 2c, one can find similarities with the ranking of gross domestic products per capita for many of the countries (Eurostat, 2017b). This does not necessarily imply that countries with relatively high GDP eat more food than others, but that the emission intensity of what is consumed could be higher. Countries with high GDP per capita like Luxembourg, Norway, Ireland, Denmark, Germany, Sweden and France all have a darker shade in the figure indicating a relative high food CF per capita, and this is consistent with the ranking of GDP per capita (Eurostat, 2017b). However, some countries' CF are not consistent with the GDP per capita, such as Greece and Lithuania indicated with relatively high CFs in Figure 2c but have relatively low GDPs, and Switzerland and Italy with relatively high GDPs are indicated with lower CFs in Figure 2c.

In Figure 2d, most of the countries have a lighter shade compared to the household food consumption per capita, showing the same trend as before with higher emission intensities in consumption than in own production. One clear difference is that Ireland is now the country with the highest impact with almost 4.5tCO_2-eq per capita per year. Looking at Irelands beef production, a connection can be made with the high amount of grazing cattle in Ireland (Reijs et al., 2013), which is subsequently related to lower efficiency in the cattle and milk production (Garnett et al., 2017), and this impacts the emission intensity of consuming own cattle products.

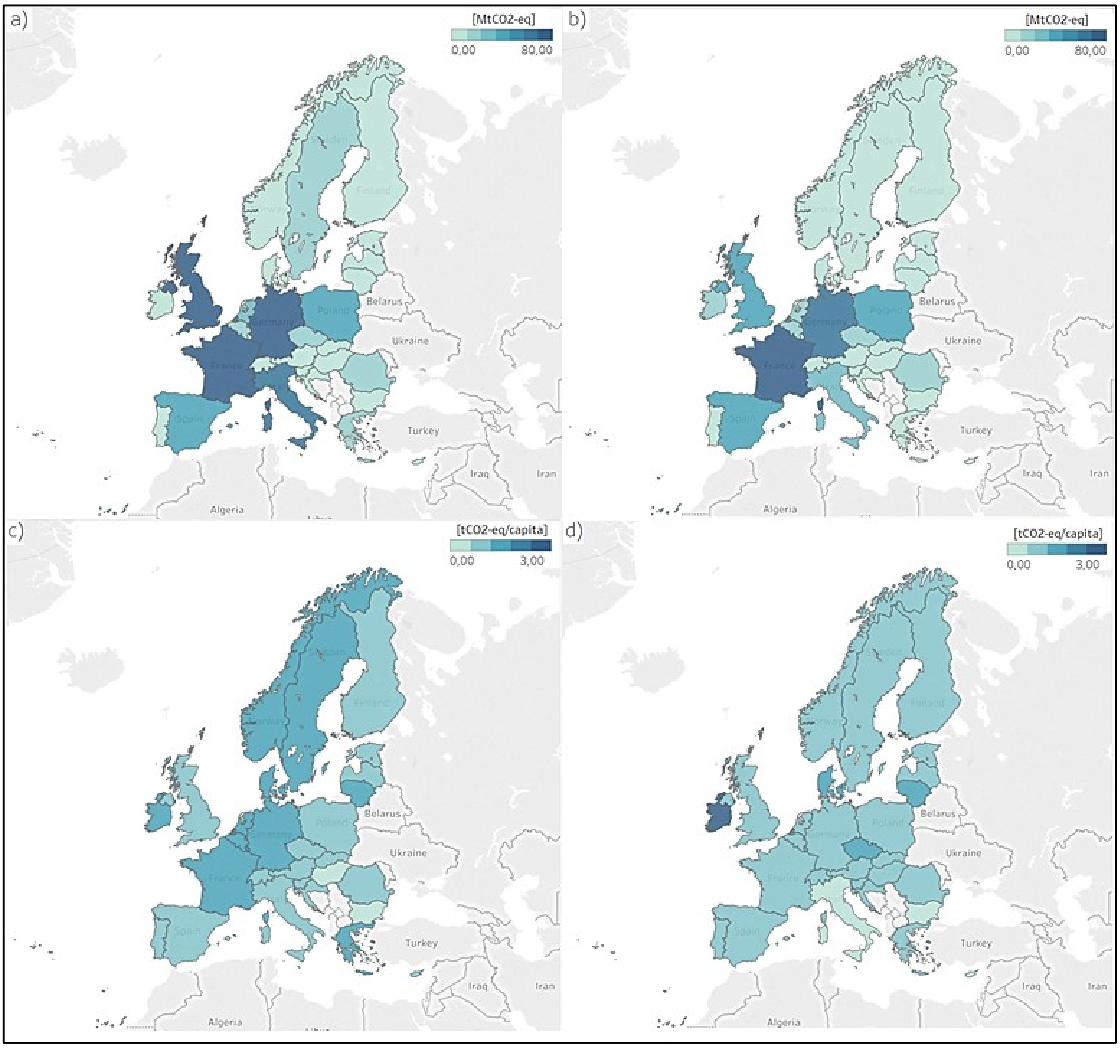

Figure 2: Environmental impact of the household food demand for the EU;a) Consumption based emissions, b) production based emissions, c) consumption based emissions per capita, d) production based emissions per capita. The figure is based on maps from open street map contributors and is made with Tableau.

The impact of household food demand in total and per capita, and for both a consumption- and a production approach were illustrated in Figure 2, but where are the emissions coming from? From now on the focus is on the emissions from the hosehold food consumption using a consumption based perspective (household food CF), like in Figure 2 a) and c). For the EU average, it is the consumption of processed food that has the largest impact followed by cattle meat and dairy. A sorted list of food industries by impact on the CF for the countries on average can be found in Appendix D.

Effects of a carbon tax

Adding a carbon tax on some of the high impacting food groups such as meat and dairy, leads to a shift in diets and consequently the CF from the diets as well, and just how much the CFs change per capita is shown on the primary axis in Figure 3, and the absolute net values are shown on the secondary axis, indicated by diamonds. Not surprisingly it is the big economies France, UK, Germany and Italy that have the highest absolute reductions in CF. France have larger net mitigations than Germany, yet Germany is a bigger economy than France. This is a consequence of a larger reduction in consumption of own cattle and dairy in France. Additionally, France had a larger price change of consumption in cattle than Germany had, which could be a contributing factor. Poland and Spain also show a high net reduction in absoulute values, however, both countries are relatively large economies as well (Eurostat, 2012), and it makes sense that significant mitigations happens also here.

As expected, the largest reductions in the CF follows lower demand of cattle related food products (beef and milk), and the increase in the CF is related to increased demand of plant based food. Ireland has the highest reduction in CF per capita related to the shift in diets, which could be connected with Irelands consumption of Irish cattle and milk, which was also indicated in Figure 2. Even though all meat and dairy products were taxed, there is mainly a reduction in the CF due to cattle and dairy, which could be related to the high environmental impact from producing cattle meat and dairy. Surprisingly Slovenia is ranked as the third largest mitigator per capita, which is a bit hard to explain, as they do not have a relatively high emission intensity on the agriculture products compared to other countries, however, Slovenia is a small country of roughly 2 millon inhabitants (Eurostat, 2012), which could contribute to larger mitigations per capita. Estonia, Czech Republic and Croatia are high in the ranking as well, however, the relatively high emission intensities of cattle and dairy industries in these countries could be a reason for that.

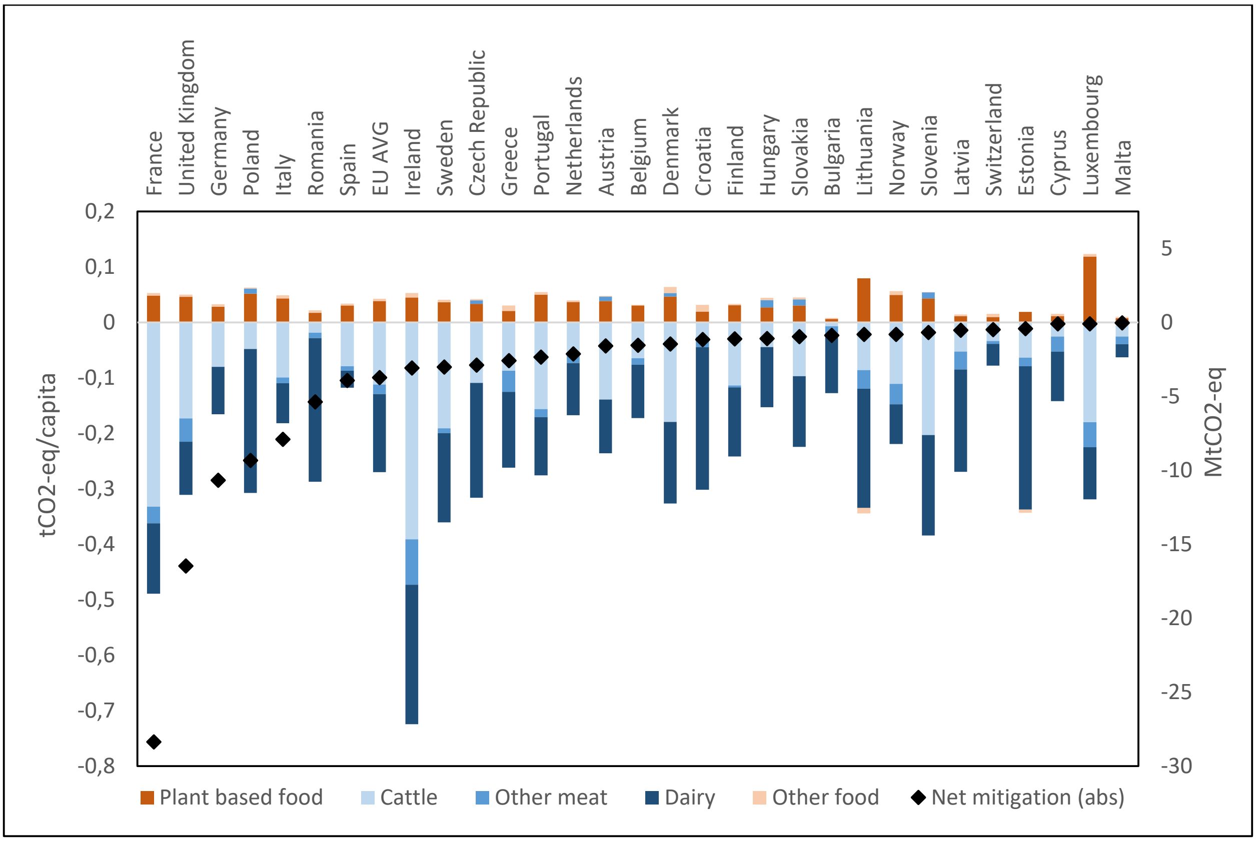

Figure 3: The change in the CF related to the shifts in diets per capita on the primary axis, and the net mitigation in absolute values on the secondary axis (diamonds)

Due to changes in consumption following an increase in prices, the diets are either more or less costly than before, depending on whether the consumer buys the taxed products or not. If the consumer now has more available money to spend, there will be a rebound effect depending on what the consumer spends the money on, thus leading to a change in demand (FD1). As the tax revenue is recycled back to the consumers by lowering income taxes, there is also a rebound effect from using the "extra" income on consumption of other goods/services (FD2). Figure 4 shows on the primary axis, the total changes in the CF on a country level due to the tax, and the rebound effects from the changed demand FD1 and FD2, as desbribed above. On the secondary axis, the total percentage change in emissions when including all three aspects for the supply tax, indicated by the black dots. For comparison, the red circles indicate the total percentage change including all three aspects when there is a demand tax.

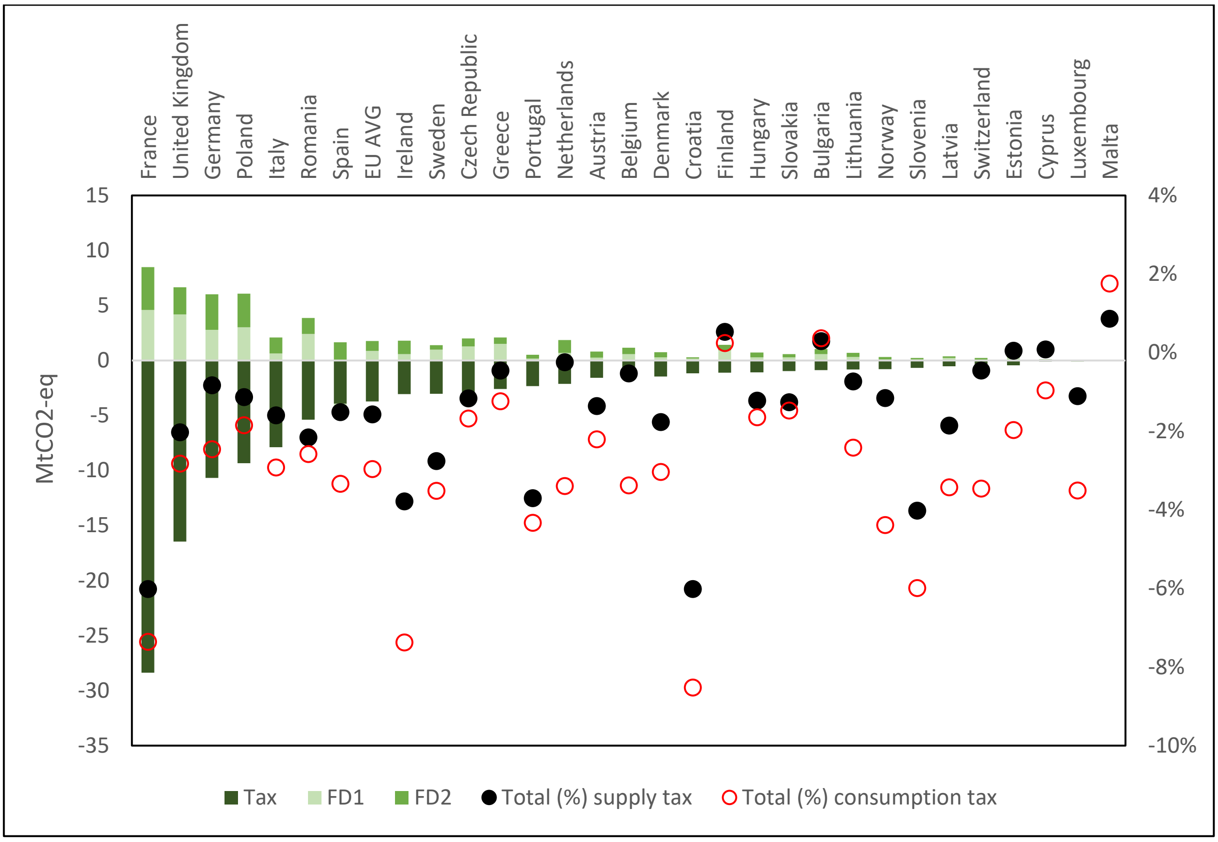

Figure 4: Change in the CF on a country level. On the left axis, changes in CF due to the tax (Tax), rebound of costlier/less costly diets (FD1) and rebound from reducing income taxes (FD2). On the right axis, the total percentage change in CF including all three factors (tax, FD1 and FD2) for both a supply tax (black dots) and a demand tax (red circles).

The countries with the highest mitigations are again the big economies like France, UK and Germany. With the exception of three countries, Finland, Bulgaria and Malta, where both Finland and Bulgaria have 0% change in CF and Malta has 1% increase, there is a net mitigation in emissions for all countries in Figure 4. Surprisingly, the largest percentage change for the supply tax is happening in Croatia with 6%. This might be due to low initial taxes on food, which could be indicated by looking at the relative price change due to the tax, where Croatia had one of the highest relative change in price for several industries (Appendix D). The total percentage reductions are in general larger with the demand tax than with the supply tax, since a demand tax also includes the emissions from non-European countries, and as Europe is a net importer of GHG emissions embodied in food, this leads a demand tax to cover bigger grounds. The difference between the supply tax and the demand tax are in some cases large, like in Ireland, Norway and Croatia, and in other cases small, like in Romania, Hungary and Slovakia. This could be related to a higher level trade with non-European countries in Ireland, Norway and Croatia compared to Romania, Slovakia and Hungary.

On average, there is a reduction of 2% for the supply tax and 3% for the demand tax, indicated in Figure 4, and comparing that to the study of Wirsenius et al. (2011) the results here are lower. Although they used a consumption tax of 60€/tCO_2 and here it was used a tax of 100€/tCO_2, they had a reduction of 7%. It is however, difficult to compare the results when the studies do not use the same method. Wirsenius et al. (2011) use cross price elasticities for only animal related food industries for instance, and thus do not include the increase of demand in plant based food illustrated in Figure 3. Nor do they look at the rebound from changes in cost of diets and rebound effects from reduced income taxes. Additionally, they assume that the land which is not used for animal feed production is used for producing biofuels, which further increases the mitigation.

Figure 5: Other effects of adding a supply tax on all animal products including tax and rebound effects indicated by the bars, the squares indicate total percentage change including all three factors

The results up until now has shown the effect of the carbon tax on the CF related to the shifts in diets, however, a tax on meat- and dairy industries does not only affect emissions, but also other socioeconomic aspects, such as employment and value added. Figure 5 shows the percentage change in the emissions in the EU, Switzerland and Norway using the production approach (contrary to the consumption approach that is used earlier) for comparison, the percentage change in employment in the EU and the percentage change in value added in the EU. The black dots represent the percentage change on average in the EU. There is a total increase in both employment and in value added, indicating that there is a shift in spending towards goods and services that generates more employment and value added than the agriculture and food sectors. Petrolium, chemicals and transport are the industries where consumers spend the largest part of their extra available money, indicating more travelling and other types of energy use. If the rebound effects were not included there would be a decrease in both employment and value added, thus indicating that including rebound effects are important to get a wider system approach.

Discussion

The resulting mitigation potential of a carbon tax on meat and dairy industries were illustrated above, indicating that there is in fact a mitigation potential. Looking at the results in Figure 4, the demand tax gives slightly higher reductions than a supply tax, which gives the demand tax an advantage in the discussion on demand tax versus supply tax. However, optimally, a carbon tax should target both the supply side and the demand side, in this way the supply side is urged to reduce their emissions making the production of food more effective, and the consumers are urged to consider what they consume and are nudged to shift towards a less emission intensive diet. Wirsenius et al. (2011) argue that there is low reduction potential on the supply side, since most of the emissions are coming from enteric fermentation. Yet, there is still a mitigation potential in changing the feed (IPCC, 2014), reducing the use of N-fertilizer (IPCC, 2014; Moran et al., 2008), or other efficiency measures, although this is not included in this thesis, as the increased cost is assumed to be fully passed on to the consumers. Adding a tax on suppliers could however, lead to a carbon leakage by increasing the imports to satisfy the demand, although the largest part of trade is already within the EU, and taxing the entire EU could lead to less market disadvantages. Nonetheless, there will always be trade with non-European countries, and this can to some degree be controlled by tariffs and alike, although, taxing imports from especially poor countries could generate negative effects in their economy, and this is not considered here.

In Figure 5, the importance of rebound effects are illustrated, as they lead to an increase in employment and in value added. Yet, the rebound effects also lead to lower mitigation than expected, as per definition, and by using the money from the tax revenue on further reductions of emissions instead of reducing income taxes, such as efficiency measures on the supply side, it could lead to a higher total reduction of emissions. Nevertheless, with the reduced income tax, there is a lower risk for regressive effects on households, since they end up with the same income as before, only their spending patterns change. There is however a risk of regressive effect on poor household that does not pay income taxes and is not included in the benefit of reduced income taxes, thus the government should perhaps consider giving some kind of compensation.

The results in this thesis are strongly dependent on the elasticities that are used, as the change in demand following price changes are directly linked to the reduction in the CF of household consumption. The most important limitation is the assumption that the EU, Switzerland and Norway have the same response to price increases as Denmark. The own price elasticities from the study of Edjabou and Smed (2013), are additionally quite high (in absolute terms) compared to the ones related to Denmark in the study of Seale et al. (2003). However, to the authors knowledge, there are no satisfactory sources in the literature that includes own and cross price elasticities of food for the different EU countries, with a satisfactory level of disaggregation.

According to the Stern Review (2007), the tax should be set equal to the social cost of emissions to be effective. But how much is clean air really worth? Or avoiding natural disasters? The social cost of emissions is clearly very hard to define. Some studies state that taxes are not as effective as anticipated because the tax rate is often set too low (Garnett, 2012). Another reason could be tax exemptions for big emitting companies, like the case of carbon tax on fuels in Norway (Bruvoll and Larsen, 2004). However, the tax rate should not be set higher than necessary, as the public will not accept an unjustified high tax. The tax rate set in this thesis is in the lower bound of the carbon prices given in literature (van den Bergh and Botzen, 2014), but some might argue that it's both too high or too low, depending on their standpoint.

As pointed out earlier, EU is a net importer of food, which could be related to the fact that an average of 45% of the utilized agricultural area in the EU 28 is dedicated to fodder production, and in Ireland, the share is over 90%, representing the country with the highest share of fodder production in the EU 28 (Eurostat, 2017a). Most of the plant based food, such as pulses, fruits and vegetables that could substitute the taxed meat- and milk products, have to be imported. This could potentially increase the amount of imports to a country, and by that lowering the country's food security. However, a tax could nudge a shift in the production output by reducing the amount of livestock and other animal products consequently reducing the amount of fodder produced to increase the food security.

The supply tax on meat and dairy will affect the farmers, and especially farmers which high production of cattle meat and dairy, as it gives the producers a financial disadvantage. One could argue that in many cases, farmers are already getting the short end of the straw when dividing the income from the retail of agriculture products and cannot afford another financial disadvantage. The consumers will also be affected by the tax in the form of increased cost of food. Cattle meat and dairy play an important role in most of the western diets, and these are the products that are most affected by the tax due to the high environmental impact. In addition to farmers and consumers, the governments could also be negatively affected of such a tax, as the tax should be revenue neutral to the government budget, which could make the tax less attractive from their perspective. Thus, there are potentially many “loosing” parties with a tax implementation on meat and dairy. However, as the AFOLU sector is responsible for one quarter of the anthropogenic GHG emissions, the government is forced to take action, and from a wider perspective, a carbon tax that leads to significant mitigations of GHG emissions will in the end benefit the whole society.

So how should the government proceed? There is much to consider when implementing a carbon tax on food, with food being a necessity in the society and the many implications such a tax could have. Nonetheless, based on the literature and the results of this thesis, some policy recommendations are attempted. From the literature, the importance of earmarking (recycling) the tax revenue is clear (Söderholm and Christiernsson, 2008; Stern Review, 2007), as it legitimizes the tax and generates higher acceptance from the public, additionally it could result in a double dividend, which is very popular amongst economists. There is also a general agreement in the literature that it is important to set the tax close as possible to the social cost of emissions to make the tax effective, credible and fair (Garnett, 2012; Söderholm and Christiernsson, 2008; Stern Review, 2007). It could also be considered to compensate the hardest affected parties, like low income households and farmers that would suffer financially from such a tax. Additionally, a strong political message of the importance of the carbon tax in advance of the implementation is also necessary to ease the process and generate understanding and support from the public.

Conclusion and future work

The aim of this thesis was to investigate if a supply tax could lead to mitigations of GHG emissions from the AFOLU sector, by targeting both the supply side and demand side, subsequently leading to less emission intensive diets. The main framework used was a MRIO analysis with the combination of several models, such as the quantity model, the price model, and a demand model, including the use of price elasticities and income elasticities. A supply tax of 100 €/tCO_2-eq was added to the meat and dairy industries in the EU, Switzerland and Norway, where the increase in cost was assumed to be passed on in its full to the consumers, in the form of higher prices of the final products in the grocery store. The tax led to a reduction in the CF for mainly cattle and dairy, which can be related to the high environmental impact of the production of these. The average reduction for the EU, Switzerland and Norway was 2%, including the rebound effects from the change in diet costs, as well as from the change in income due to the reduced income taxes funded by the tax revenue. For comparison with similar grounds, a demand (consumption) tax obtained on average 3% reduction of the GHG emissions. The supply tax additionally led to a small increase in both employment and in value added of 0.4% and 0.7% respectively.

To the authors knowledge, there has not yet been an implementation of a carbon tax targeting both supply and demand, with the aim of reducing GHG emissions. It is anticipated that implementing such a tax could receive negative feedback, both from the producers and the consumers of meat and dairy. Although many are aware of the high impact from producing these, it is not something most people consider in their daily life, as food is a necessity. The diets are often founded in the culture or social norms of the country, and it can be hard to accept an increased cost of this. However, from a government perspective, it is important to reduce emissions where possible, and when the AFOLU sector represents one quarter of the anthropogenic emissions, measures must be taken. With a carbon tax targeting both the supply and demand, the responsibility is shared, and could be perceived as more fair. Additionally, the increase in employment and value added could ease the implementation from a policy perspective.

As the results are strongly based on the price elasticities that are used, where the assumption is that all of the EU, Switzerland and Norway have the same price response as Denmark, the results have large uncertainties, as described in the section “Data and limitations”. Future work could therefore be to model own and cross price elasticities as well as income elasticities for each of the countries in the EU plus Switzerland and Norway, and in that way have one source for all elasticities, which would, by far, raise the relevance of the results in this thesis. Other future work could be to model how much of the increase in prices the suppliers would pass on to the consumers with a supply tax and analyze the effects, as the assumption in this thesis is that all increase in cost is passed on to the consumers.

Appendix A

The quantity model is used to model the absolute change in total output **x** after adjusting either the intermediate demand **Ax** or the final demand **y**. A derivation of the production model, including the environmental impact **F**, heavily based on the derivation from the unpublished project thesis of Stakvik et al. (n.d) and the IO theory from Miller and Blair (2009) follows:

If we sum across the rows from each sector *i* to each sector *j*, where *j* goes from 1 to *n* sectors, and the final demand for sector *i,* we get the total output in sector *i*, given in equation (19):

$$\mathbf{x}_i = \sum_{j=1}^{n} \mathbf{z}_{ij} + \mathbf{y}_i \tag{19}$$

Or, we can write the total output it in matrix notation, as in equation (20):

$$\mathbf{x} = \mathbf{Zi} + \mathbf{y} \tag{20}$$

Where **i** (industries x 1), represents a column vector of ones. This enables us to sum **Z** into a vector so that we can add it together with **y**. The **A**-matrix (industry x industry), is a requirement matrix and contains information of the intra-industry requirements to produce one unit of output, e.g. a_{1j} tells us the requirements from process 1 to process *j* to produce one unit of total output from *j*.

$$\mathbf{A} = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix}$$

Equation (21) gives us the relationship between **Z** and **A**, where $\hat{\mathbf{x}}$ is the diagonalized **x**-vector:

$$\hat{\mathbf{x}} = \begin{bmatrix} x_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & x_n \end{bmatrix}.$$

$$\mathbf{Z} = \mathbf{A}\hat{\mathbf{x}} \tag{21}$$

If we insert equation (21) into equation (20), we get the production model given in equation (22), where $\mathbf{x}$ is the total output, $\mathbf{Ax}$ is the internal demand, and $\mathbf{y}$ is the final demand.

$$\mathbf{x} = \mathbf{Ax} + \mathbf{y} \tag{22}$$

By rearranging equation (22) we get equation (23), where **I** (industries x industries) is the identity matrix:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \tag{23}$$

Using the definition for Leontief inverse:

$$\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1} \tag{24}$$

And finally insert equation (24) in equation (23), we get the following:

$$\mathbf{x} = \mathbf{Ly} \tag{25}$$

Where the **L**-matrix, or Leontief inverse, shows the total requirements needed to produce one unit final demand. The element l_{1j} of L represents the output from industry 1 required to deliver one unit of industry *j*'s output to final demand.

$$\boldsymbol{L} = \begin{bmatrix} l_{11} & \cdots & l_{1n} \\ \vdots & \ddots & \vdots \\ l_{n1} & \cdots & l_{nn} \end{bmatrix}$$

To include pollution impacts related to industry activity, a matrix of direct impact coefficients **S** [s_{kj}] can be defined, where k is the type of pollutant per euro output of industry j. Adding the direct impact coefficient to the total output, the environmental impact **F** [impact x industries]**,** can be defined as:

$$\mathbf{F} = \mathbf{SL\hat{y}} \tag{26}$$

Where $\mathbf{\hat{y}}$ is the diagonalized of $\mathbf{y}$.

Appendix B

The price model can be used to model relative changes in price after a modification of either the value added **v'** or the requirement matrix **A**. In this study, we use the price model to calculate the changes in price after a tax is added to certain industries. Following, is a derivation of the price model heavily based on the derivation from the unpublished project thesis of Stakvik et al. (n.d) and the IO theory from Miller and Blair (2009).

If we sum down column *j* of **Z** and **v'**, we get the total input, which should equal the total output if everything is accounted for. For sector *j*:

$$\mathbf{x}_{\mathrm{j}} = \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathbf{z}_{\mathrm{ij}} + \mathbf{v}'_{\mathrm{j}} \tag{27}$$

Or, we can write in matrix notation as in equation (28), here we see that the **x**-vector is transposed since we are summing the **Z**-matrix column-wise.

$$\mathbf{x}' = \mathbf{i}'\mathbf{Z} + \mathbf{v}' \tag{28}$$

Further, we insert equation (21) in equation (28) and post-multiply with $\hat{\boldsymbol{x}}^{-1}$, then we get:

$$\mathbf{x}'\mathbf{x}^{-1} = \mathbf{i}'\mathbf{A}\hat{\mathbf{x}}\hat{\mathbf{x}}^{-1} + \mathbf{v}'\hat{\mathbf{x}}^{-1} \tag{29}$$

Alternatively, we can write it as in equation (30):

$$\mathbf{i}' = \mathbf{i}'\mathbf{A} + \mathbf{v_c}' \tag{30}$$

Where $\mathbf{v_c}' = \mathbf{v}'\hat{\mathbf{x}}^{-1}$. Right side, $\mathbf{i}'\mathbf{A} + \mathbf{v_c}'$, is the cost of inputs per unit of output. Output prices are set equal to total cost of production; thus we end up with a vector of ones. If the base year cost is indexed with $\tilde{\mathbf{p}}'$(1 x industries), we get the price model:

$$\tilde{\mathbf{p}}' = \tilde{\mathbf{p}}'\mathbf{A} + \mathbf{v_c}' \tag{31}$$

By rearranging equation (31) ,we get:

$$\widetilde{\mathbf{p}}' = \mathbf{v}_\mathbf{c}'(\mathbf{I} - \mathbf{A})^{-\mathbf{1}} = \mathbf{v}_\mathbf{c}'\mathbf{L} \tag{32}$$

As the column vector of prices, $\widetilde{\mathbf{p}}$ (industry x 1), is more used we transpose equation (32) and get:

$$\widetilde{\mathbf{p}} = (\mathbf{I} - \mathbf{A}')^{-1}\mathbf{v}_\mathbf{c} = \mathbf{L}'\mathbf{v}_\mathbf{c} \tag{33}$$

Appendix C

Table 2: Own and cross price elasticities (Edjabou and Smed, 2013)

Food products	Milk	Cheese	Curdled	Eggs	Other dairy	Butter	Margarine	Beef	Fish	Pork	Other meat	Poultry	Sliced meat	Canned fish	Flour and bread	Sugar	Biscuits and cakes	Other foods	Fresh vegetables	Frozen vegetables	Fruit	Potatoes	Rice and pasta
Milk	-0.477	-0.260	-0.080	-0.313	-1.167	-0.095	-0.045	-0.131	-0.062	-0.232	-0.051	-0.072	0.633	0.202	0.282	0.091	0.064	0.109	-0.266	-0.060	-0.251	-0.080	-0.052
Cheese	-0.181	-1.213	-0.364	-0.328	-0.658	-0.095	-0.045	-0.131	-0.062	-0.232	-0.051	-0.072	0.633	0.202	0.282	0.091	0.064	0.109	-0.266	-0.060	-0.251	-0.080	-0.052
Curdled milk	0.497	-0.326	-0.983	0.540	-0.520	-0.095	-0.045	-0.131	-0.062	-0.232	-0.051	-0.072	0.633	0.202	0.282	0.091	0.064	0.109	-0.266	-0.060	-0.251	-0.080	-0.052
Eggs	0.043	0.220	0.613	-1.422	-0.241	-0.095	-0.045	-0.131	-0.062	-0.232	-0.051	-0.072	0.633	0.202	0.282	0.091	0.064	0.109	-0.266	-0.060	-0.251	-0.080	-0.052
Other dairy	-5.528	8.149	-1.492	0.048	-1.664	-0.095	-0.045	-0.131	-0.062	-0.232	-0.051	-0.072	0.633	0.202	0.282	0.091	0.064	0.109	-0.266	-0.060	-0.251	-0.080	-0.052
Butter	-0.110	-0.129	-0.034	-0.032	-0.006	-1.083	-0.441	0.380	0.181	0.673	0.148	0.210	0.863	0.275	0.099	0.032	0.022	0.038	-0.705	-0.158	-0.665	-0.212	-0.138
Margarine	-0.110	-0.129	-0.034	-0.032	-0.006	0.701	-1.032	0.380	0.181	0.673	0.148	0.210	0.863	0.275	0.099	0.032	0.022	0.038	-0.705	-0.158	-0.665	-0.212	-0.138
Beef	-0.494	-0.578	-0.154	-0.144	-0.026	0.004	0.002	-1.184	0.048	0.521	-0.508	0.086	-0.599	-0.191	0.016	0.005	0.004	0.006	0.477	0.107	0.450	0.143	0.093
Fish	-0.494	-0.578	-0.154	-0.144	-0.026	0.004	0.002	0.447	-0.794	0.428	-0.543	0.122	-0.599	-0.191	0.016	0.005	0.004	0.006	0.477	0.107	0.450	0.143	0.093
Pork	-0.494	-0.578	-0.154	-0.144	-0.026	0.004	0.002	0.078	-0.222	-1.178	-0.462	-0.219	-0.599	-0.191	0.016	0.005	0.004	0.006	0.477	0.107	0.450	0.143	0.093
Other meat	-0.494	-0.578	-0.154	-0.144	-0.026	0.004	0.002	-0.179	-0.455	1.456	-1.007	0.267	-0.599	-0.191	0.016	0.005	0.004	0.006	0.477	0.107	0.450	0.143	0.093
Poultry	-0.494	-0.578	-0.154	-0.144	-0.026	0.004	0.002	0.473	0.088	0.484	-0.017	-1.438	-0.599	-0.191	0.016	0.005	0.004	0.006	0.477	0.107	0.450	0.143	0.093
Sliced meat	0.048	0.056	0.015	0.014	0.003	0.163	0.077	-0.030	-0.014	-0.054	-0.012	-0.017	-1.030	-0.499	0.085	0.027	0.019	0.033	0.067	0.015	0.063	0.020	0.013
Canned fish	0.048	0.056	0.015	0.014	0.003	0.163	0.077	-0.030	-0.014	-0.054	-0.012	-0.017	0.605	-0.993	0.085	0.027	0.019	0.033	0.067	0.015	0.063	0.020	0.013
Flour and bread	0.686	0.803	0.214	0.200	0.036	-0.319	-0.150	-0.108	-0.051	-0.191	-0.042	-0.060	-0.688	-0.219	-0.954	-0.349	-0.393	-0.482	-0.154	-0.035	-0.145	-0.046	-0.030
Sugar	0.686	0.803	0.214	0.200	0.036	-0.319	-0.150	-0.108	-0.051	-0.191	-0.042	-0.060	-0.688	-0.219	0.433	-0.926	-0.074	-0.139	-0.154	-0.035	-0.145	-0.046	-0.030
Biscuits and cakes	0.686	0.803	0.214	0.200	0.036	-0.319	-0.150	-0.108	-0.051	-0.191	-0.042	-0.060	-0.688	-0.219	0.418	0.009	-1.029	0.107	-0.154	-0.035	-0.145	-0.046	-0.030
Other foods	0.686	0.803	0.214	0.200	0.036	-0.319	-0.150	-0.108	-0.051	-0.191	-0.042	-0.060	-0.688	-0.219	0.407	-0.133	-0.041	-1.078	-0.154	-0.035	-0.145	-0.046	-0.030
Fresh vegetables	-0.048	-0.056	-0.015	-0.014	-0.003	-0.121	-0.057	0.066	0.032	0.117	0.026	0.037	0.342	0.109	-0.277	-0.090	-0.063	-0.107	-0.852	-0.366	0.078	-0.018	-0.821
Frozen vegetables	-0.048	-0.056	-0.015	-0.014	-0.003	-0.121	-0.057	0.066	0.032	0.117	0.026	0.037	0.342	0.109	-0.277	-0.090	-0.063	-0.107	0.285	-1.150	0.321	0.164	-0.031
Fruit	-0.048	-0.056	-0.015	-0.014	-0.003	-0.121	-0.057	0.066	0.032	0.117	0.026	0.037	0.342	0.109	-0.277	-0.090	-0.063	-0.107	0.201	-0.323	-1.087	-0.675	0.026
Potatoes	-0.048	-0.056	-0.015	-0.014	-0.003	-0.121	-0.057	0.066	0 .032	0.117	0.026	0.037	0.342	0.109	-0.277	-0.090	-0.063	-0.107	1.134	0.052	-1.090	-0.575	-0.091
Rice and pasta	-0.048	-0.056	-0.015	-0.014	-0.003	-0.121	-0.057	0.066	0.032	0.117	0.026	0.037	0.342	0.109	-0.277	-0.090	-0.063	-0.107	-1.920	-0.005	2.135	-0.003	-0.559

Table 3: Correspondence matrix between the labels from EXIOBASE and those of Edjabou and Smed 2013

EXIOBASE labels || Edjabou and Smed labels	Rice and pasta	Flour and bread	Fresh vegetables	Sugar	Beef	Pork	Poultry	Other meat	Milk	Fish	Other food
Cultivation of paddy rice	1										
Cultivation of wheat		1									
Cultivation of cereal grains nec		1									
Cultivation of vegetables, fruit, nuts			1								
Cultivation of oil seeds											
Cultivation of sugar cane, sugar beet				1							
Cultivation of plant-based fibers											
Cultivation of crops nec											
Cattle farming					1						
Pigs farming						1					
Poultry farming							1				
Meat animals nec								1			
Animal products nec											
Raw milk									1		
Wool, silk-worm cocoons											
Manure treatment (conventional), storage and land application											
Manure treatment (biogas), storage and land application											
Fishing, operating of fish hatcheries and fish farms; service activities incidental to fishing (05)										1	
Processing of meat cattle					1						
Processing of meat pigs						1					
Processing of meat poultry							1				
Production of meat products nec								1			
Processing vegetable oils and fats											
Processing of dairy products									1		
Processed rice	1										
Sugar refining				1							
Processing of Food products nec											1
Manufacture of beverages											
Manufacture of fish products										1	

Appendix D

Table 4: Top 20 relative changes in price after the supply tax implementation with and without price cap (nec =not elsewhere classified)

Countries	Industries	Relative change in price	Relative change in price with cap
Finland	Meat animals nec	394 %	60 %
Croatia	Cattle farming	279 %	60 %
Croatia	Raw milk	256 %	60 %
Luxembourg	Cattle farming	211 %	60 %
Norway	Meat animals nec	174 %	60 %
Slovakia	Cattle farming	139 %	60 %
Lithuania	Cattle farming	118 %	60 %
Czech Republic	Cattle farming	115 %	60 %
Sweden	Cattle farming	101 %	60 %
Ireland	Cattle farming	93 %	60 %
Latvia	Cattle farming	93 %	60 %
Spain	Cattle farming	91 %	60 %
Estonia	Cattle farming	74 %	60 %
Sweden	Meat animals nec	72 %	60 %
Belgium	Meat animals nec	70 %	60 %
Denmark	Meat animals nec	68 %	60 %
Hungary	Cattle farming	63 %	60 %
Croatia	Pigs farming	60 %	60 %
Slovakia	Processing of meat cattle	59 %	59 %
Spain	Meat animals nec	54 %	54 %

Table 5: Ranking of each of the industries' impact on the baseline household food CF for the EU on average, when looking at consumption based emissions, given in MtCO2-eq (nec =not elsewhere classified)

Industries	EU AVERAGE
Processing of Food products nec	5,23
Processing of meat cattle	2,58
Processing of dairy products	2,36
Cultivation of vegetables, fruit, nuts	1,45
Manufacture of beverages	1,28
Manufacture of fish products	0,96
Processing of meat pigs	0,73
Cattle farming	0,61
Raw milk	0,60
Processing of meat poultry	0,47
Poultry farming	0,42
Cultivation of wheat	0,39
Meat animals nec	0,35
Cultivation of paddy rice	0,34
Fishing, operating of fish hatcheries and fish farms; service activities incidental to fishing (05)	0,28
Production of meat products nec	0,28
Cultivation of oil seeds	0,20
Cultivation of cereal grains nec	0,20
Cultivation of crops nec	0,18
Processing vegetable oils and fats	0,13
Sugar refining	0,13
Processed rice	0,08
Pigs farming	0,04
Animal products nec	0,02
Cultivation of plant-based fibers	0,02
Cultivation of sugar cane, sugar beet	0,01
Wool, silk-worm cocoons	0,00
Manure treatment (conventional), storage and land application	0,00
Manure treatment (biogas), storage and land application	0,00

Appendix E

An excel file with additional data and information is provided digitally as supplementary information.

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