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Economy-wide analysis of food waste reductions and related costs

A global CGE analysis for the EU at NUTS-II level

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Abstract

Reducing food waste has become a policy priority in recent years as many studies show that a significant amount of food is wasted at various stages of the food supply chain. However, the economic impacts of food waste reduction have not been studied in depth as most of the studies in the literature ignore the cost and feedback effects. The aim of this report is to develop a general framework to analyse the economic impacts of reducing food waste in EU28 in both a global and a regional context in support of the EU policy making process on food waste reduction. For the purposes of this study, we employ the CGEBox toolbox which is a flexible, extendable, and modular code basis for CGE modelling. The default configuration of CGEBox used in this study covers the global economy with a detailed representation of the agriculture and food production sector whereas the EU28 is modelled at NUTS-II level.

The impact of a food waste reduction equal to 5% of the intermediate input use of food processing sectors under two different cost assumptions is analysed in the scenarios. Firstly, in the *cost neutral* scenario, we assume that the cost of reducing food waste is equal to the monetary savings for the food processing industry. Secondly, in the *pessimistic* scenario, we assume that the cost of reducing food waste is twice as much as the cost savings made by reducing food waste.

The results suggest that a unilateral commitment by the EU to reducing food loss and waste would most likely decrease the competitiveness of the EU's food processing. Reduced demand for primary agricultural inputs would shrink the EU's agricultural sectors, putting pressure on farm incomes and land prices. The contribution to global food security would be very minor. The impact on emissions relevant to climate change at global level is also minor, with a very limited contribution within the EU.

1 Introduction and background

1.1 Background

The Directorate of Sustainable Resources of the European Commission's Joint Research Centre (JRC) provides the scientific knowledge for European Union (EU) policies related to the sustainable use of resources and related socio-economic aspects. The focus is on food security, land, soil, water, forest, bio-diversity, critical raw materials, and related ecosystem services; on highlighting the threats to our existing resources and to exploring alternatives such as those related to oceans; on monitoring and analysing agricultural production; and on supporting the development of a sustainable bio-economy in Europe. The Directorate mainly serves Agricultural and Rural Development, Development and Cooperation, Environment, Maritime Affairs and Fisheries policy areas but also supports policies related to climate change, growth, and trade.

The Economics of Agriculture Unit of the Directorate of Sustainable Resources provides scientific support to the EU policy-makers in assessing, through macro and micro socio-economic analyses, the development of the Agricultural and Food (Agrifood) sector and related sectors, including rural development, food security, trade, and technological innovation in the EU and globally, with special emphasis on Africa. This support is based on advanced economic modelling tools, statistical methods, and easy access to data.

1.2 Policy background

The literature on food waste has grown rapidly in recent years and is now vast. It clearly shows that a significant part of food production is wasted at different stages of the food supply chain (FSC). Two influential studies, namely Monier et al. (2010) and FAO (2014a), highlight the importance of food waste reduction in the debate on how to sustainably feed the world. According to Monier et al. (ibid.), around 90 million tons of food is wasted annually, corresponding to 12% of total global food production. While post-harvest loss rates show peaks in selected FSCs of developing countries, the shares of waste from OECD countries such as the EU are also prone to being considerable.

Consequently, reducing food waste has become a priority in the European Union. On the one hand, the European Commission has set a target of halving food waste throughout the EU by 2020 in order to make Europe more resource efficient while contributing to global food security (European Commission; 2015,2011). On the other hand, the European Parliament (2018) voted for "the EU should meet a non-binding 30% target for food waste cuts by 2025, rising to 50% by 2030". Lastly, The European Council adopted conclusions on food losses and food waste in June 2016. The Council has called on "Member States and the Commission to improve monitoring and data collection to improve understanding of the problem, to focus on preventing food waste and losses, to enhance the use of biomass in future EU legislation, and to facilitating the donation of unsold food products to charities" (European Council, 2016). Furthermore, in a recent farm council meeting the EC Health Commissioner mentioned that the Commission is "reflecting on how a reformed Common Agricultural Policy (CAP) could help reduce food losses & waste by stimulating more efficient production, processing, and storage practices and the evolution towards a circular bio-economy". Hence, policies aiming at reducing food waste could become important drivers of change in the agri-food sector.

This study aims to develop a framework to analyse the economic impacts of reducing food waste in EU28 from both a global and a regional perspective.

The report is organized as follows. First, a brief review of the literature is presented, where the many definitions of food waste are also summarized and discussed. Then, scenarios and modelling approach will be presented. Presentation of the results follows in section 4. The last section is reserved for concluding remarks.

1.3 Definition of food waste

Almost every study in the literature starts with a discussion about the definition of food waste and concludes that there is no consensus. The only agreement seems to be on what is not considered to be food waste, namely:

- What is consumed by humans as food is not food waste.
- What is not produced as food cannot be food waste when wasted or lost.

However, the discussion on the definition of food waste is actually about the details rather than the core of the subject. The discussions centre on the following "axes":

- **Loss vs waste**: Many earlier definitions in the literature tend to separate food waste from food loss (see for example: FAO, 2012; Lipinski et al., 2013; BCFN, 2012; FAO, 2011). Food loss is generally attributed to the earlier stages of FSC such as production and processing while waste is attributed to later stages such as retail and household consumption (e.g., because of the behavioural characteristics of consumers; see FAO, 2011) and technological constraints (Filho and Kovaleva, 2015). However, food waste and loss have recently started to be used as synonyms (Betz et al., 2015). Most studies conserve the wording "Food waste and loss" but do not make any distinction between them in terms of treatment (see for example: HLPE, 2014). The disappearance of the distinction can be attributed to the different moral tones that these two words have: Loss is more "innocent or unintentional" while waste is "evil or intentional" (Chaboud and Daviron, 2017).
- **Human consumption vs non-human consumption**: Some FAO documents count food that is directed to animal feed as food waste (FAO, 2014a; FAO, 2014b; FAO, 2011) while other authors argue that since food diverted to animal feed can be seen as a transformation of food to livestock products, it cannot be considered to be food waste (Chaboud and Daviron, 2017). In fact, many argue that diverting non-consumed food to animal feed is a good solution for food waste (FAO, 2014c). Indeed, FAO (2014c) changes the former FAO definition of food waste by excluding food diverted to animal feed as food waste (Bagherzadeh, Inamura, and Jeong; 2014).
- **Excess consumption**: Some studies tend to include over-eating as food waste (BCFN, 2012; Smil, 2004). However, most studies do not consider "Food that is consumed in excess of nutritional requirements" as waste (FAO, 2014b).
- **Avoidable vs. non-avoidable**: Some UK studies introduced the concept of avoidable and non-avoidable food waste (Ventour, 2008; WRAP, 2009). Unavoidable food waste is "waste deriving from the preparation of food or drinks that are not, and could not, be edible (for example, meat bones, egg shells, pineapple skins, etc.)". On the other hand, avoidable food waste is "food and drinks that are thrown away despite still being edible (for example, slices of bread, apples, meat, etc.)" (Ventour, 2008). However, some practical implications of this split are quite questionable because only the "by-products that are useful and marketable product" are counted as waste (Filho and Kovaleva, 2015). Furthermore, as "unavoidable" food waste does not have any real economic value, it does not make sense, at least from the economic point of view, to call these 'residues' waste.

- **Pre-Harvest vs post-harvest**: Some consider food wasted or lost at pre-harvest stage as part of the food waste (FAO, 2014b; HLPE, 2014) while others do not. Particularly in the US, food waste is mostly considered to be a waste management problem, and so the focus is on post-harvest losses and waste (USDA, 2018).

Along with the above axes, quite different definitions are given for food waste (Teuber and Jensen, 2016). Each definition leads to differences on how to quantify total waste and so its economic, social, and environmental impacts, and related to that, the costs of reducing it. In turn, these costs would determine some 'optimal amount of food waste'. However, for the purposes of this study, it may not be necessary to rely on an exact definition. Here what matters more is the percentage of food that is wasted at different stages of the Food Supply Chain. For example, if both avoidable and non-avoidable waste are included in the definition (and so food waste accounting), inedible parts of the food products should also be included in production, which in return should not change the overall percentage of food waste. As this study considers different stages of the FSC separately, considering the food transformed into animal feed as food waste or not, considering pre-harvest losses or not, etc. should not influence the analysis beyond the feedback effects. In addition, the costs related to food waste reduction can be expected to change according to the scope of different definitions. However, as we link the costs to the benefits of the food waste reduction for each specific definition (i.e., the wider the scope, the larger the benefit and hence the larger the cost), our main findings should be rather robust for the chosen definition of food waste.

Why then is a common definition important? Depending on the scope of the definitions, any policy action will have very different implications for different actors in the FSC. Therefore, a common definition is necessary from a legal point of view (Vaque, 2015). One recent definition of food waste that was given by the European Parliament as a recommendation to the Commission and Member States to use is as follows (Caldeira, Corrado, and Sala, 2017):

> "food waste means food intended for human consumption, either in edible or inedible states, removed from the production or supply chain to be discarded, including at primary production, processing, manufacturing, transportation, storage, retail, and consumer levels, with the exception of primary production losses."

This definition excludes the pre-harvest losses from the food waste and does not consider food diverted to animal feed to be waste (as these foods would not be discarded from the FSC but diverted within it). Furthermore, it does not count excess consumption as waste, and it does not make any distinction between losses or waste or where the waste occurs in the FSC.

1.4 Amount of Food waste

Research on the quantification of food waste is quite large but also segmented in terms of what is considered to be food waste (Bagherzadeh, Inamura, and Jeong; 2014), how it is measured, which segments of FSC are taken into account, and the geographical location at which the waste is considered (Xue, et al., 2012). It therefore mirrors the different definitions discussed above. This makes comparison of the different studies, even for the same year and country, quite difficult. Although the estimates differ substantially, the common agreement is that food waste accounts for a substantial amount of the food produced or consumed. Some early estimates range between 30 to 60% for developing countries and 15 to 25% for developed countries (Engström and Carlsson-Kanyama, 2004). However, they are mostly based on the

FAO food balance sheets, and for this reason have been criticized by many academics (Smil, 2000; Wirsenius, 2000).

Commissioned by the EC-DG-ENV, the study by Monier et al. (2010) is the first to present food waste estimates at the Member State level and has therefore become a reference for the EU. The study reports annual food waste in the EU ranging from 50kg per capita in Greece to 180kg per capita in the Netherlands. This adds up to 90 million tonnes of food waste for the EU, or 42% of all food produced in the European FSC (Secondi, Principato, and Laureti; 2015). However, these figures have been subsequently challenged. In a report prepared for the European Parliament, Priefer, Jörissen, and Bräutigam (2013) calculate different amounts of food waste and different contribution levels for each segment of FSC to the overall food waste in individual Member States. They argue that Monier et al. (ibid.) "generally underestimates the HH food waste". Furthermore, Secondi, Principato, and Laureti (2015) calculate food waste in the EU using data from the so-called "Flash Eurobarometer 2013" survey and report contradicting figures compared to Monier et al. For example, while in Monier et al. the Netherlands is the country that produces most waste at household level, Secondi, Principato, and Laureti report a figure for this country which is below the EU average. Gjerris and Gaiani (2013) estimate that food waste in Nordic countries is almost half what is reported by Monier et al., while Katajajuuri et al. (2014) report almost 30% higher food waste for Finland. On the other hand, a number of studies carried out for some member states (e.g., Vanham et al., 2015) support the estimates reported by Monier et al.

The first global estimation of food waste incidence (FAO, 2011) indicates that 30% of food is wasted globally, with differences across countries. Figures in this study have become a reference for many studies on food waste but have also been criticized for both underestimation and overestimation. Bräutigam, Jörissen and Priefer (2014) compare the results of Monier et al. and the FAO concluding that "results differ significantly, depending on the data sources chosen and the assumptions made. Further research is much needed in order to improve the data stock, which builds the basis for the monitoring and management of food waste".

Bagherzadeh, Inamura, and Jeong (2014) compile a database for food waste and loss by considering estimates for OECD countries from different sources. The database contains information on amounts of waste for different food products, wastage at different FSC stages, when available by year, using harmonized units. Although incomplete and not updated since 2014, the database is the only standardized source of information on food waste for developed countries.

There is also literature focusing on specific production stages, possibly on specific countries or regions, or on specific food products. Xue et al. (2012) present a detailed review of 202 such studies that reports food waste for 84 countries and 52 individual years. They conclude that most studies only cover a few countries and are based on secondary data, which questions their reliability. In general, the micro level studies, e.g. studies run for a specific company, school, village, canteen etc., reports much higher waste ratios compared to the macro studies described above (Xue et al., ibid.). Again, this is probably because of the differences in food waste definitions and measurement methods used. Reutter, Lant, and Lane (2017) conclude that, "it is very difficult to harmonize individual level observations with large-scale calculation based estimations due to problems with data collection process and reaching a representative sample".

1.5 Causes of food waste

Many contributions focus on identifying the causes of food waste. However, as the numbers of studies analysing the causes of food waste surged, the inevitable conclusion started to appear: food waste and loss is driven by many causes which are often interrelated (Teuber and Jensen, 2016). The main drivers can be classified in four broad categories: technology; marketing and sales strategies; consumer habits; and market conditions.

Technological inefficiencies causing food waste are mostly related to the production and distribution infrastructure such as limitations on agricultural, transport, and storage infrastructure (BCFN, 2012), insufficient training for farmers, or premature harvesting (Bagherzadeh, Inamura and Jeong; 2014). These inefficiencies mostly cause waste or loss at some earlier stages of the FSC. Many of the technology related causes of food waste are difficult or costly to eliminate because they would require substantial investment.

Marketing and sales strategies are also blamed for causing or increasing – or at least not helping to reduce – the food waste. Packaging size and quality, portion size choice by restaurants, labelling that incites consumers to discard products sooner, discount bundling in the super-markets, quality sorting, preference over disposing rather than re-using, and unnecessary stocks are all reported to cause food waste (Monier et al., 2010; Beretta et al, 2013; Bagherzadeh, Inamura and Jeong, 2014; BCFN, 2012; Gooch, Felfel and Marenick, 2010).

Many studies seem to agree that most of the waste occurs at the retail stage so suggested explanations are related to consumer habits. Over purchasing, wrong storage, lack of confidence on leftovers; undervaluing/not caring about food waste; education level and socio-economic background; and the frenetic modern life style are among the behavioural habits blamed for food waste (BCFN, 2012; Gooch, Felfel and Marenick, 2010; Monier, et al., 2010; Jörissen, Priefer and Bräutigam, 2015; Kibler et al., 2018; Parizeau, Massow and Martin, 2015).

The last set of factors causing food waste is market conditions (broadly considered). Over production and/or low demand, low food prices, and low labour costs are among the factors that lead to what some authors term an "inefficient" market equilibrium (Beretta et al., 2013; Bagherzadeh, Inamura and Jeong, 2014; FAO, 2014a). A second set of market factors relates to the legal framework, which determines the incentives for the agents in the food markets: unclear responsibility of food donors (Planchenstainer, 2013), waste management frameworks that are not suitable for food (Bagherzadeh, Inamura and Jeong, 2014), and lack of incentives for cooperation in FSCs to reduce food-waste (Bagherzadeh, Inamura and Jeong, 2014; Gooch et al, 2010; Filho and Kovaleva, 2015). Among these, coordination along the FSC is one often emphasized cause.

While the effect of these factors on food waste is intuitive, especially for marketing and consumer habit related factors, evidence on their actual relevance is not conclusive. For example, findings on the impact of labelling are mixed. For instance, it was found that the term "use by" causes 50% more waste than the term "best by" or "sell by" (Wilson et al, 2017). Koivupuro et al. (2012) report that socio-economic background, education level, shopping, food preparation, and eating habits do not correlate with food waste levels in Finland.

1.6 Impacts of Food Waste

Wasted food inevitably impacts on the society, the economy, and the environment due to both direct costs, i.e. inputs and factors used to produce it, and related opportunity costs and externalities. Furthermore, in a world where hunger is still a major problem, food waste is also a question of social justice (Beretta et al, 2013) as reducing food waste might increase the access of the undernourished to food (FAO, 2011; BCFN, 2012). FAO (2014d) estimates the monetary value of these social costs of food waste to be $882 billion USD.

Literature exists which focuses on the environmental impacts of food waste, giving quite detailed results, for example, on GHG emissions, water, and land use. The FAO (2013) estimates that 3.3 Gtonnes of CO2-equivalent is emitted to produce the wasted or lost food. For the EU, Monier et al. (ibid.) estimate that 3% of total GHG emission is due to wasted food. Therefore, avoiding food waste is also considered to be a mitigating measure against climate change (FAO, 2014c).

The production of waste food is estimated to consume around 250 km^3 of water (FAO, 2013); some estimates go up to as much as 23% of total water use (Kummu et al., 2012). This is higher than the municipal water consumption or green water use for cereal production in Spain (Vanham et al., 2015). Therefore, food waste would definitely have far reaching implications for the so-called Food-Water-Energy nexus (Kibler et al., 2018).

Waste food production is also reported to cover 30% of total crop land globally, with important implications for soil degradation, soil erosion, and land use change such as pressure on rain forests (FAO, 2014d).

Naturally, waste food also indirectly accounts for a significant part of agricultural input use, such as fertilizers and pesticides, which impact on health or on the environment, e.g. nitrogen pollution from fertilizers, bio-diversity loss from pesticides (FAO, 2013), (Pretty, 2005). Related costs are estimated to be high. For example, Vanham et al. (2015) show that total nitrogen used to produce the wasted food is more than the nitrogen used in UK and Germany combined. Hall et al. (2009) estimate the energy used in the USA to produce the wasted food is equivalent to 300 barrels of oil.

Unfortunately, evidence on the economic impacts of food waste is quite scarce. FAO (2014d) offers a global annual monetary assessment of wasted food at 2,625 billion USD. Of these, 1,000 billion USD is the estimated direct value of the waste food, i.e. immediate economic cost. The social costs linked to hunger not avoided amount to 882 billion, of which the bulk with 396 billion USD are the social cost due to higher risk of conflict caused by food shortages. The remaining costs of 700 billion USD are linked to environmental impacts with GHG emissions (305 billion USD) and water (164 billion USD) as the most important items. Clearly, these estimates are even more uncertain than the underlying food waste estimations.

These estimates should not be confused with marginal impacts, which can be quite different. There are two simple reasons for that: first, food waste reduction is costly and preventive measures themselves are likely to have some environmental impacts (Chaboud & Daviron, 2017). For example, cold storage facilities would consume energy, donating excess food to food banks would require transportation of food, and better packaging might require the use of more materials that are harmful to the environment. Secondly, the food types that are generally the most wasted might not have the highest impact on environment. For example, meat has a high environmental impact but compared to bread or fruit its waste and loss rate is generally lower.

1.7 Economics of Food Waste

Economic analyses of food waste are in short supply (Teuber and Jensen, 2016; Chaboud and Daviron, 2017). Studies that are based on economic reasoning generally focus on the economic costs of food waste and benefits of the reduction of food waste but the trade-offs are rarely taken into account in a systematic way.

Rutten (2013) presents the first rigorous implementation of economic theory to analysing the impacts of food waste reduction in a partial equilibrium setting and concludes that the impacts are likely to be ambiguous and stresses the need to quantify the impacts. The study successfully sketches the framework that could be used in an economic analysis of food waste reduction but in the absence of data, it remains somewhat hypothetical. Costs related to food waste reduction are mentioned, but they are not part of the framework. For example, investments in cold storage facilities would require using more energy in the FSC and this is likely to change the slope of the line on the supply graph, with implications for the graphical analysis presented in Rutten (2013).

Model-based studies employ different types of tools, such as CGE models at the country level (Campoy-Munoz, Cardenete, and Delgado, 2017; Britz, Dudu, and Ferrari, 2014) or at global level (Rutten et al., 2013; Rutten and Verma, 2014; Rutten and Kavalari, 2016), trade models (Munesue, Masui, and Fushima, 2015), partial equilibrium models (Höjgård, Jansson, and Rabinowicz, 2013), or econometric methods (Ellison and Lusk, 2016). Rutten et al. (2013) and Campoy-Munoz, Cardenete, and Delgado (2017) focus on down-stream stages of production while Rutten and Verma (2014) and Rutten and Kavalari (2016) pay attention to earlier stages, i.e. harvest losses. Although the assumptions and the structure of these models are different, almost all studies report the following main findings: (1) significant economic benefits and reduced environmental impacts from agricultural production; (2) improved food safety (Rutten and Verma, 2014; Rutten and Kavalari, 2016; Munesue, Masui, and Fushima, 2015); (3) declines in agricultural production; and (4) limited impacts on GDP (Rutten et al. 2013; Campoy-Munoz et al, 2017)). For example, Rutten et al. (2013) report that 5% to 9% of household income and 1.6% of total EU agricultural land would be saved due to food waste reduction while Munesue, Masui, and Fushima (2015) estimate that food waste reduction would decrease the number of undernourished people by 63 million in developing countries. The only exception that shows only marginal environmental and economic benefits is Höjgård, Jansson, and Rabinowicz (2013) who link food waste to low food prices and consider the value of time for households.

These pioneering studies have made significant contributions. In particular, they have introduced quantitative economic analysis to the food waste literature. However, with the exception of Britz, Dudu, and Ferrari (2014), all other studies assume that food waste and loss reduction is costless and thus is like "manna from heaven". In contrast, Britz, Dudu, and Ferrari (2014) simulate food waste reduction (like other studies) as a reduction in agricultural intermediate inputs used in home cooking and food processing sectors, but also assume that this reduction would require labour and capital. They simulate the impact in a regional CGE model for the Netherlands, introducing a household food production sector, which requires both the household's time – competing with leisure and labour outside the household - and bought food. Their results show that costs associated with efforts to reduce food waste significantly change the magnitude of economic impacts.

The few studies in the literature which try to explain food waste on the basis of economic behaviour are generally sceptical about the benefits of food waste reduction. These studies argue that food loss and waste must be a rational decision based on economic costs and benefits of food waste reduction (Koester, 2014; Ellison and Lusk, 2016). Consequently, they offer a different view that associates food waste to the inability of economic agents to implement waste reducing measures, possibly because of irrational behaviour, asymmetric information, or organizational problems (FAO, 2014c). Recent findings in the literature support this economic reasoning. For example, Salemdeeb et al. (2017) reports that 60% of the GHG reductions due to food waste prevention are offset by GHG created by prevention measures. Furthermore, Höjgård, Jansson, and Rabinowicz (2013) find quite limited environmental impacts of food waste reduction even when the related costs are not taken into account.

Teuber and Jensen (2016) introduce the concept of "optimal food waste" which is reached when marginal cost of food waste reduction equals to the marginal "benefit" of food waste. Although they do not quantify this optimal amount, the basic idea reflects the typical view of economic analysis. Accepting this view has important implications: when setting food waste reduction targets, an economically optimal amount should be identified as higher targets would be inefficient. As emphasized by Teuber and Jensen (2016), "more research is needed to assess how the prevention of food loss and waste (FLW) can lead to a more resource-efficient food system by particularly investigating how costly it might be to reduce FLW and which trade-offs might occur among different stakeholders".

Finally, economic studies also shed light on some distributional effects of food waste reduction. Once the costs and trade-offs are taken into account, food waste reduction will have distributional impacts by redistributing wealth/income among different regions and economic agents. An important issue such as food security is, to a large extent, a question of purchasing power. Both Campoy-Munoz, Cardenete, and Delgado (2017) and Höjgård, Jansson, and Rabinowicz (2013) report quite different impacts across countries or regions of the same country as well as between producers and consumers. The net effect of food waste reduction efforts in one region depends on many factors such as food trade balance, or the elasticity of demand and supply. The impact assessment study by the European commission on EU waste management targets also confirms that food waste reduction would benefit manufacturers while food producers and retailers are likely to be worse-off (European Commission, 2014).

2 Scenario design

Food waste and loss occur in different segments of the supply chain, covering the production sectors of primary agriculture, the manufacturing sector i.e., the sector that processes and prepares food for distribution, the wholesale and retail sectors that distribute the output of the food processing industry to households, caterers, canteens, restaurants etc. and the final point of use, i.e. the household, restaurants etc. The majority of studies show that most of the food waste and loss occur during food processing and at household level. For example, Monier et al. (2010) report that 42% of food waste in Europe occurs at household level and 39% in food processing, while the distribution food service sectors account for between 5% and 14% of food waste and loss. However, their study does not cover wastes and losses at the production stage of primary agricultural products. Similarly, Stenmarck, Jensen, and Quested (2016) find that 53% of food waste is at the household level, 19% during processing, 10% in the primary production sector, 12 % in the food service sector, and 5% in the distribution sector; with varying numbers across member states. Similar results are also found in a study by Beretta et al. (2013) for Switzerland which states that 45% of the waste and loss is at household level while food processing follows with 31%.

The recent study by Britz, Dudu, and Ferrari (2014), employing the RegCGEEU+ model, mainly focuses on food waste at household level, considering the efforts necessary to reduce food waste such as spending more time on food preparation. Technically, it introduces a new sector in the SAM which uses time – competing with leisure and work outside the household – and intermediate inputs. Drawing on time use data at household level for the Netherlands, the authors conduct a single country study without depicting interactions with other regions or considering environmental impacts.

The current study complements that work by focusing on the food processing industry. Like Britz, Dudu, and Ferrari (2014), it is assumed here that food waste reductions do not come for free. For the food industry, primary agricultural inputs constitute an important part of production costs so that it is not very likely that the intermediate input demand for this input will be reduced without incurring other costs. Accordingly, it is also assumed that, in order to reduce the primary agricultural input, the use of other inputs has to increase. The reasoning of Teuber and Jensen (2016) of "optimal food waste" is consequently followed by assuming that the current input mix of the food processing industry is cost minimal.

As there is limited evidence about how costly it could be to avoid food waste at industry level across all food processing sectors, we consider two scenarios which should cover the relevant range of assumed costs. Both assume that 5% of agricultural inputs in the food industry, measured in quantitative terms, could be saved as follows:

1. **Cost-neutral**: The first scenario assumes cost-neutrality, i.e. that the cost-savings to the industry by reducing primary agricultural inputs are exactly offset by the additional costs incurred by increasing other inputs. The calculation is done at the benchmark prices;
2. **Pessimistic**: While assuming the same 5% reduction agricultural inputs as in the cost-neutral scenario, the pessimistic scenario assumes that each Euro saved as agricultural inputs leads to two Euros of additional costs in other inputs, again at benchmark input composition and prices.

Technically, the changes are implemented as non-Hicks neutral technical progress by updating input-output coefficients and cost share parameters. This implies that the 5% savings in quantitative terms are not necessarily found in the simulation results since the production technology is not Leontief, i.e. production inputs are not perfect complements but substitution between different inputs as well as between the value-added and the intermediate composite is possible. If agricultural product prices fall as a consequence of the shock, agricultural input use in the food processing sectors will decrease and offset part of the assumed change in technology, that is, following the food waste reduction if agricultural inputs become cheaper compared to other inputs and factors of production, food processing firms can re-increase the amount of agricultural input they use to reduce the use of more expensive substitutes based on their production technology.

3 Modelling approach

3.1 Modularity

Modularity is generally understood to be the degree to which a system's components may be separated and recombined. More specifically, in CGE modelling it implies that software components depicting specific economic and bio-physical transformations might be added on demand, such as modules for environmental accounting or the modules as system components might be exchanged so that, to provide an example, different methodological approaches to trade modelling are supported without re-programming. Technically, a module is a block of software code with a clearly defined interface allowing the user to shift between different configurations. Modularity for a CGE therefore implies that it can be configured differently without the need to reprogram part of its code.

Most well-known CGEs are hardly modular but can be termed flexible to a certain degree. Flexibility can be understood in the sense that selected elements in the overall model layout can be adjusted while components are not exchanged. The most popular example of such flexibility are different closures where the partitioning of endogenous and exogenous variables changes. Another example is CET and CET nests where the substitution elasticity can take any value between zero, i.e. the Leontief case and infinite, i.e. the law of one price. This type of flexibility is found in the ENVISAGE model (van der Mensbrugghe, 2008) from which it is carried over to CGEBox.

One of the best-known examples of a modular CGE model is MAGNET (Woltjer et al., 2014). Its development reflects the wish to use a core base model in different configurations instead of having multiple independent versions which share a larger part of the code without being properly synchronized. MAGNET mainly draws on modules which are intellectual property right (IPR) protected in-house developments from various projects, partly around the former LEITAP (Banse et al., 2011) model. These modules mostly relate to agri-food issues such as support for production quotas, to (partially) separate factor markets for agriculture and non-agriculture, land supply, and CET-allocation nests for land, a biofuel blending module, or a module for the CAP. MAGNET and LEITAP were also used in studies looking at longer-term developments so some modules specifically focus on features related to recursive-dynamic CGE modelling.

The basic idea of MAGNET provided the conceptual starting point for the development of CGEBox but with two differences. Firstly, CGEBox aims to develop modules which are mostly extensions developed by the GTAP centre and released as open source versions of the GTAP standard model. Secondly, MAGNET draws on GEMPACK which does not feature a flexible pre-processor to support conditional includes[1] so the MAGNET team developed its own pre-compiler for GEMPACK. CGEBox is coded in GAMS, which supports modularization more easily. Moreover, the Gams Graphical User Interface Generator (GGIG) developed by Britz (2014) is used to steer the modular framework because it has been used for a longer time with other models in which extensions can be switched on and off.

Table 1 below reports core modules in MAGNET and CGEBox and shows the somewhat different foci of the two modular CGE tools. As mentioned above, MAGNET has a strong focus on the agricultural sector and to some degree on the CAP, while CGEBox shows more flexibility with regard to resource use (GTAP-AEZ, GTAP-WATER, Non-CO2 emissions) and allows for different options to model international trade. The main

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[1] An excellent comparison between GAMS, GEMPACK and MPSGE is provided by Horridge and Pearson (2011).

advantage of module availability in CGEBox for this project is that it features sub-national detail for Europe at NUTS2 level.

Table 1: Comparison of availability of core modules in MAGNET and CGEBox

	MAGNET	**CGEBox**
Separation of agr and non-agr factor markets	+	Part of GTAP-AGR
Nutrition accounting	+	-
CET nests of land supply	+	Can be implemented based on flexible nesting
CAP	+	-
Land supply	+	Factor supply functions in template
Biofuels	+	-
Adjusted consumption pattern	+	Part of G-RDEM model available with CGEBox
Production quotas	+	Upper bound on output with MCP
Dixon investment module	+	-
GTAP-Water	-	+
GTAP-E	?	+
GTAP-AEZ	-	+
GTAP-HET	-	+
NUTS2	-	+
myGTAP	+	+
MRIO	-	+
Non-CO2 emissions	?	+
Different functional forms for final demand	?	+
CES sub-nests in demand	-	+
Single country template	-	+

Source: Authors' elaboration

3.2 Scalability

Scalability is often understood in the sense that a CGE model can be applied to databases with different levels of detail to yield models which are identical in structure but are different in size. Algebraic modelling languages such as GEMPACK and GAMS support scalability based on their set driven concept so data transformations and equations entering model instances are defined on flexible lists of regions, commodities, agents etc. However, it should be noted that the specific data requirements of modules often define lower limits on the resolution with regard to regions, factors, and commodities. In CGEBox, the NUTS2 resolution requires that the EU is depicted by individual Member States while GTAP-AEZ and GTAP-WATER demand land and water as separate factors, respectively. Some of the specific nestings used in GTAP-AGR and GTAP-E only make sense if detail in agricultural and energy sectors is introduced into the database.

However, the definition of scalability focusing on supporting databases with different levels of details falls short in a key aspect of the more general meaning of scalability, namely, that a process can handle a growing amount of work. GEMPACK automatically substitutes out variables from the log-linearized model which can lead to situations where it completely outperforms GAMS when a model is scaled in size and the GAMS solver runs against memory limits (Horridge and Pearson, 2011). Here, CGEBox introduces features to reduce memory and processing time needed in GAMS such as an algorithm which reduces the size of the global SAM by removing tiny entries, a feature which allows substitution of variables which grow non-linearly in model size, and a pre-solve algorithm. These options are all used in the current study (see also Britz and Van der Mensbrugghe, 2016).

3.3 CGEs with sub-regional detail and European coverage

The impact of agricultural and agri-environmental policies depends to a large degree on location factors such as climate, soils, or slope. For a long time this has been reflected in supply-side and partly in the partial equilibrium models by sub-national dis-aggregation. Prominent examples of regionally dis-aggregated modelling system for Europe can be found in The Common Agricultural Policy Regional Impact (CAPRI) (Britz and Witze, 2012) and the Global Biosphere Management Model (GLOBIOM) (Valin et al., 2013). Economic geography has underlined that location clearly matters beyond primary sectors, but sub-national detail is often still missing in CGE models and when found, it is often in single country CGEs. Indeed, there are currently only three CGE models which offer both European coverage and sub-national detail.

The first of these models is the so-called Regional Holistic Model (RHOMOLO) (Mercenier et al., 2016) which became operational in 2010. Its main purpose is to analyse questions more generally related to regional development across the EU. The model is recursive-dynamic in nature and uses exogenous saving rates. It currently covers the 267 NUTS2 regions of the EU27, and each region is disaggregated into five sectors (agriculture; manufacturing and construction; business services; financial services and public services) plus a national research and development (R&D) sector. Goods and services are either produced under perfectly competitive markets or under imperfect competitive sectors as according to Krugman (1991). Preferences in each region are characterized by the Armington price index in conjunction with perfectly competitive sectors, and by a Dixit -Stiglitz price index in conjunction with non-competitive sectors. Labour markets feature a wage graph to capture endogenous unemployment. However, land is not treated as a separate factor. Modelling food waste and more general agricultural or food related issues is basically impossible with RHOMOLO as there is solely one aggregated agricultural sector while manufacturing and construction is another sectoral aggregate which includes the food processing industry.

The CAPRI – The Rural Development Dimension (CAPRI-RD) project developed comparative-static single country CGE models with NUTS2 resolution (RegCgeEU+; Britz, 2012) which cover 11 sectors for all EU member states including accession countries based on a single regionalized country CGE template originally developed for Finland (Rutherford and Törmä, 2010). It has some features similar to RHOMOLO such as regional government and private household accounts as well as a wage graph, but does not depict intra-regional bi-lateral flows between all NUTS2 regions in Europe as RHOMOLO does, but only distinguishes between regional, national, and imported origin. The model was applied by Britz et al. (2014) to analysing food waste scenarios at both industrial and household level for the Netherlands. The model only features one agricultural sector which reflects the aim of coupling it with the CAPRI partial equilibrium model with its rich agricultural detail to jointly analyse the first and second pillars of CAP instruments.

Both modelling tools are therefore not developed for detailed analysis of agricultural and agri-food related issues as reflected in their sectoral breakdown and also seen in the fact that RHOMOLO does not treat land as a separate factor. Leaving the question of sub-national detail aside, the GTAP database here provides a more natural starting point to analysing questions relating to agri-food value chains with 12 sectors relating to agriculture, separate forestry and fishing sectors as well as 8 food processing sectors, and some more sectors related to the processing of agricultural outputs. Furthermore, extensions such as GTAP-AEZ or GTAP-WATER depict resource use in agriculture.

If questions relating to resource use and global spillovers are the focus and not regional policy analysis, a separate regional government account and final demand at regional level are not necessary, as found in RHOMOLO and CgeRegEU+. Abstracting from these separated regional government accounts and final demands therefore reduces model complexity. CGEBox only dis-aggregates the production and factor supply side of the economy to sub-national detail. Demand and income distributions and therefore reduces model complexity. SAMs from both the RHOMOLO and the CAPRI-RD project could be used to dis-aggregate the EU part of the GTAP database thanks to their NUTS2 resolution. Although older, the SAMs from the CAPRI-RD have the advantage of featuring eleven rather than five sectors at regional level and offer more detail for the analysis of agri-food related issues, namely differentiation between agriculture, forestry, and other primary sectors, a separate food processing sector, and one for hotels and restaurants. The SAMs underlying the RegCgeEU+ model were therefore chosen as the basis for the NUTS2 breakdown of the GTAP database in CGEBox. In order to improve the dis-aggregation for the agri-food sectors, they are combined with data from the regional CAPRI database. Specifically, the output value shares from CAPRI for the individual crop and animal production activities at regional level are used as split factors for primary agriculture. For example, the food processing industry is linked to primary agricultural sectors so raw milk production shares for each region are used to estimate the dairy production share of that region.

Table 2: Comparison of key features of CGEBox, RHOMOLO V2, and RegCgeEU+

	CGEBox	**RHOMOLO V2**	**RegCgeEU+**
Basic template	Global trade model based on GTAP, comparative-static or recursive dynamic	EU regionalized at NUTS 2 level versus Rest of the World, recursive-dynamic	Single country, regionalized at NUTS2 level for each EU Member State and Accession country, comparative-static
Sectoral detail	Up to 57 sectors, the SAMs with 11 sectors from RegCgeEU+ are integrated based on split factors from CAPRI database for agriculture and food processing; otherwise proportionality	5 sectors	11 sectors
Factors	Land and water are treated separately	Land and water presumably aggregated with capital	Land is treated separately, water not covered
Sub-national trade	-	Fully bi-lateral between NUTS2 regions in the EU	Only distinction between regions, nations, and imported origins.
Final demand	National	Regional	Regional
Taxes and government account	National	National and regional	National and regional
Trade modelling	2-nested Armington, Krugman, Melitz; imported/domestic shares agent specific, alternatively MRIO	1 nested Armington, Krugman, extended Krugman; equal shares across agents	Armington; equal shares across agents
Agricultural, environmental, and resource use related extensions	GTAP-AEZ, GTAP-Water, CO2 and NON-Co2 emissions, possibility to distinguish agricultural and non-agricultural households		

Source: Authors' elaboration

Table 2 reports the main differences between the three models. If food waste questions are not only analysed with regard to welfare impacts but also with regard to environmental and resource use issues, and impacts on countries or country groups beyond the EU such as developing countries, then CGEBox is clearly the most suitable choice. The main dis-advantage compared to the specialized regionalized models is that the regional accounts for private household and government are missing. However, CGEBox features factor use and related prices at NUTS2 level by sector, which allows income generation at uniform national tax rates to be depicted at the regional level. In addition, RHOMOLO allows intra-regional trade between all NUTS2 regions in Europe to be depicted, while CGEBox only depicts bi-lateral trade at the level of nations, it allows dis-aggregation of the non-EU countries into many countries or country blocks.

3.4 Market structures

3.4.1 Options to depict international trade in CGEBox

CGEBox allows international trade to be depicted based on four different methodological choices. The Armington assumption as the first option is the most commonly used, differentiating products by region of production, i.e. origin, using a CES-utility function. All major CGE models use at least a two-stage Armington system with different substitution elasticities between the domestic and import origin and between individual importers. However, they differ in terms of differentiation by agent. By way of example, in the GTAP Standard model, the shares in the top-level nests are agent specific, i.e. different for each production sector and each final aggregate demand agent. The second example, GLOBE, removes that differentiation completely. However, the GTAP database does not offer agent specific bi-lateral trade shares. This data, named Multi-Regional Input-Output (MRIO), is to some degree available in CGEBox thanks to shares provided by the METRO model of the OECD. CGEBox offers the choice of using the GTAP standard layout, where the different Armington agents (production sectors, private household, government, savings) have different import and domestic shares, or the GLOBE layout where all these shares are identical, or intermediate solutions. The MRIO extension aggregates all intermediate demanders, but also uses agent specific shares for the bi-lateral trade relations. A frequent complement to the Armington assumption is the use of identically structured CET nests to distribute supply, an option also supported by CGEBox.

A not widely used option to depict international trade in CGE models is the use of the Krugman and Melitz approaches, both available in CGEBox. MIRAGE is the only well-known CGE model employing the Krugman formulation. It has been widely used for impact assessment of trade policy in studies for the EU Commission. While Krugman assumes fixed costs for a firm entering a sector, Melitz expands the model through trade link specific fixed costs. The resulting decreasing constant returns to scale, which would favour the emergence of monopolies, and is offset by assuming intra-sectoral product differentiation leading to firm specific prices, love of variety by the consumers as well as productivity distribution across firms. Introducing these features leads to additional mechanisms not depicted by the Armington model. By way of example, bi-lateral trade liberalisation allows less productive firms to start trading, benefitting consumers because more varieties are available, while the expansion of bi-laterally traded quantities distributes the fixed costs of trade over larger quantities. Opposite impacts are observed in the domestic market following the increased competition from imports. The Melitz extension of CGEBox is explained in Jafari and Britz (2018).

3.4.2 Default market structure for the current project

The default configuration for CGEBox for the current project is based on the extensions explained below. With regard to international trade, all markets use the MRIO extension, i.e., bi-lateral import shares differ between intermediate demand, government demand, final demand, and investment. An aggregation of intermediate demand in the top level nests fits that formulation so imported and domestic shares are identical across the sectors.

This also helps to reduce the numerical complexity related to the application of the Melitz extension (for details on the Melitz extension, see http://www.ilr.unibonn.de/em/rsrch/CGEBox/GTAP_Melitz.pdf) which is applied to five food processing sectors (cattle meat, other meat, dairies, beverages and tobacco, other food industry) and five industrial sectors (textiles and apparel, chemicals, petroleum and coke, light manufacturing, and heavy manufacturing) and one service sector (Trade, which is mostly retail). Sugar, rice, and oilseed processing as well as leather processing are depicted as competitive sectors as are all primary and all services, with the exception of the so-called trade service sector which includes retail and wholesale in the GTAP database. Following the set-up by Akgul et al. (2016), the Melitz extension introduces a separate fixed cost nest, with a higher share of value added. The shape parameter of the Pareto distribution of firm productivity is chosen as 4.6. The two-stage Armington configuration is used for all competitive sectors, which is complemented by a two-stage CET (Constant Elasticity of Transformation) approach which distributes regional output to the domestic market and exports (first stage) and to the various export destinations (second stage).

3.5 Production function nesting and factor supply

CGE models such as the GTAP Standard model, GLOBE, or MIRAGE make different assumptions about the degree to which inputs can be substituted against each other and basically completely relies on nested CES functions (see Table 3 below). Variants of GTAP such as GTAP-E introduce additional nests. CGEBox supports a flexible nesting approach based on sets definitions, which also eases the task of replicating more complex nesting structures without the need to add equations and variables manually. A similar approach based on nested CET structures is also available for factor supply.

Table 3: Overview of production function nesting in the different models

	Production function nesting		
Model	**Value Added – Intermediate composite**	**Intermediate composite**	**Value Added**
GTAP Standard	Leontief	Leontief	CES
GLOBE	Leontief	CES	CES, with sub-nest for skilled/unskilled labour
MIRAGE	Leontief	CES	CES, with capital-skilled labour sub-nest
ENVISAGE	CES	CES with sub-nests for energy	CES, skilled-unskilled labour nest

Source: Authors' elaboration

The default production function configuration of CGEBox in the current study is composed of the following structure:

1. The intermediate and value added can be substituted against each other (*"gams\parameters\ND_VA.gms"*) with moderate elasticity.
2. The same holds for inputs inside the intermediate nests (*"gams\parameter\IO_SUBS.gms"*).
3. Intermediates classified as feed inputs into livestock activities can be substituted more easily against each other as part of the **GTAP-AGR** module. The same holds for agricultural inputs into the food processing sectors.
4. According to **GTAP-E**, there is multi-level nesting structure for energy intermediates. The top level nests substitute energy against capital as a sub-nest of the Value Added composite.
5. As part of GTAP-E, skilled and unskilled labour are considered to be partial substitutes.

6. The fixed costs of production and trade depicted in the Melitz model, i.e. for non-competitive sectors, comprise a higher share of primary factors compared to the variable ones. However, the intermediate composite in the fixed and variable cost nests share the nestings described in points 1-5 above.

The following defaults are used for factor supply:

1. Natural resources are assumed to be immobile.
2. According to the **capital vintage module**, non-depreciated capital is considered immobile and newly formed capital is mobile.
3. For all primary factors, including new capital, there is sluggish factor supply between agricultural and non-agricultural sectors as part of GTAP-AGR at national level.
4. Land and water are considered regionally immobile in the **NUTS2** module whereas the other factors are considered to be sluggish when moving between regions within a nation.
5. In addition, land cannot move across Agro-Ecological Zones (AEZ) according to the **GTAP-AEZ** module, and NUTS2 regions are broken down AEZs. Furthermore, GTAP-AEZ introduces a nested CET-approach to land in different agricultural uses.
6. Irrigation water supply is assumed to be sluggish (see *"gams\extenions\water_nest.gms"*).

Factors stocks at the national level and, where applicable at regional level, are considered to be fixed. The only exceptions are: (1) irrigation water in non-water-constrained regions (see the next chapter for a detailed discussion), (2) new capital, which is equal to gross investments according to the capital vintage module.

3.6 Database detail and configuration

The database is set up as follows:

- Based on GTAP9-Water, i.e., water as separate primary factor and the distinction between **irrigated and non-irrigated production activities.**
- 25 single EU member States plus a residual aggregate, 9 regional aggregates for non-EU regions: North America, Latin America, Middle East and North Africa, Sub-Saharan Africa, East Asia, Southeast Asia, South Asia, Oceania, and the Rest of the World.
- **Full sectoral detail for agriculture** (including irrigated/non-irrigated distinction; paddy rice, wheat, other grains, oilseeds, fruit and vegetables, sugar beet/cane, fibre crops, other crops, ruminants for cattle, raw milk, wool, other animal products) **and food processing** (ruminant meat, other meat, dairy products, paddy processing, sugar, oilseed processing, other food industry, beverages, and tobacco).
- Remaining sectors highly aggregated, but with some important detail for the bio-economy (leather, textiles, lumber) and as intermediate providers to agriculture (chemicals, coke, and petroleum).
- **Non-diagonal make** to remove the split-up in irrigated/non-irrigated commodities found in GTAP-WATER, but keeping irrigated/non-irrigated activities dis-aggregated.
- Moderate filtering of raw GTAP-AGG output (1.E-10 absolute, 1.E-5% relative).
- The 21 EU regions (Finland, Sweden, Denmark, United Kingdom, Ireland, Germany, Netherlands, Belgium, France, Austria, Spain, Portugal, Italy, Greece, Poland, Bulgaria, Romania, Slovakia, Slovenia, Czech Republic, Hungary) which comprise NUTS2 data are dis-aggregated regionally to **NUTS2**;

Other EU countries in the dataset as single countries are: Estonia, Latvia, Lithuania, Croatia; remaining EU28 aggregate: Cyprus, Malta, Luxembourg.
- **GTAP-AEZ** breakdown also implemented for NUTS2 regions, using land use information from CAPRI regional data and some GIS work.
- **NUTS2 SAMs** (originally comprising only one agricultural sector) enriched by data on regional production value of agricultural activities from CAPRI database; meat, sugar, paddy rice and milk processing linked to related primary agricultural production value at regional level.

Other details in the configuration:

- Accounting for CO2-Emissions and Non-CO2 Emissions
- **MyGTAP**: Distinction between agricultural and non-agricultural households, based on factor income shares; separate government account
- Post-model aggregation to continents and EU28; crops/animals/food processing/all industry sectors
- Trade in VA indicators based on calculating the global Leontief inverse

3.7 Closures and numeraires

As in GTAP standard, i.e.:

- Fixed exchange rate as regional numeraire
- Global factor prices index as world numeraire (Walras' law)
- Private household and government adjust spending
- Global bank mechanism closing trade balance

A separate closure file ("*gams\scen\closures\water.gms*") defines a list of NUTS2 regions where irrigation water is not judged to be constrained so that it is not a fixed stock, but a fixed price is introduced. For details on modelling water, see section "Natural resources and environmental accounting".

3.8 Model size and solution strategy

CGEBox offers some flexibility on how to solve the model. The current project used the following options.

- Global scaling factor for GTAP database 1000
- Minimal scaling factor for variables in model is 1.E-3
- 1 round of pre-solves for single countries, in memory grid parallel (Solvelink=6)
- No intermediate solve of trade side; only Full model solved as a CNS in CONOPT4 (parallel)
- Armington quantities (but not prices) are substituted out, import/domestic prices are substituted out

The resulting model size is about 505,000 equations and variables. This model takes about 6.5 minutes to find the solution on a Laptop with an Intel I7-6500U CPU @2.5 GHZ and 8 GB RAM using GAMS 25.0, of which 3 minutes are spent on post-model processing. Time spent increases considerably when the global Leontief inverse for the Trade in Value Added (TiVA) extension and related indicators are calculated.

3.9 Natural resources and environmental accounting

Natural resources are accounted for in CGE/IAM models (Integrated Assessment Models) in various ways. As primary resources, their rent enters the value added of some resource dependent industries and their availability constrains the supply. For instance, endowments of natural resources are indirectly estimated in the GTAP database on the basis of given industry supply elasticities. Secondly, some natural resources are “hidden” production factors because they are not marketed and their contribution cannot be properly assessed on the basis of economic accounts. Finally, natural resources are affected in various ways by economic activities and it is often important to evaluate the “footprint” of the economy on the environment. From the modelling perspective, environmental data complement the economic, but environmental variables do not affect the general equilibrium unless markets for primary resources are created as part of a policy.

A thorough discussion of the modelling of natural resources is beyond the scope of this report. The following briefly illustrates two specific cases and how they are implemented in CGEBox: water and greenhouse gas emissions. These two cases are representative of non-marketed factors (water) and auxiliary variables with possible inclusion in the market functioning (emissions).

3.9.1 Water

Calzadilla et al. (2016) discuss the issue of modelling water resources in CGE models in full. In essence, two main approaches are found in the literature. One approach interprets water as an implicit factor, whose availability is reflected in variations of the total factor productivity, especially in agriculture. The second approach elicits a price for water as part of the value and rent of land. These two approaches are somewhat in line with two water management schemes: the first is consistent with water interpreted as a public, non-market good (prevalent in Europe) whereas the second is more coherent with the so-called “riparian doctrine” for water rights (prevalent in the U.S.A.). At the moment, the second methodology is implemented in CGEBox although there are in principle no major difficulties in considering exogenous variations in productivity.

Data on irrigated agriculture is provided by a special version of the GTAP9 database termed “GTAP-Water” (Haqiqi et al., 2016). For the purposes of CGEBox, the so-called diagonal version of the database is used, which can be aggregated by GTAPAgg. That version not only splits crop activities into irrigated and non-irrigated ones, but also the related outputs, thus not only differentiating “irrigated wheat” from “non-irrigated wheat” in production, but also in demand and trade. It is therefore recommended that the aggregation facility built in the data driver of CGEBox to aggregate the irrigated and non-irrigated commodity back into one category is used so the distinction between rainfed and irrigated in the model is only found at the production stage.

The integration of irrigation water into CGEBox has been enhanced by the project for the NUTS2 resolution in two ways. Firstly, data on irrigated areas at NUTS2 level from Eurostat is integrated in the construction of the NUTS2 SAMs. When the GTAP-Water database was used in the past, the national share of irrigated and non-irrigated crops in the total output found in the SAM was used to split the estimated regional output based on CAPRI data. In contrast, these shares now reflect the regional data from Eurostat which are stored in GAMS format under “*gams\GTAPNuts2\NUTS2_irr_area.gms*”.

Secondly, a distinction between water stressed and non-water stressed regions has been introduced. In the latter case, it is assumed that the amount of irrigation is currently not limited, which implies infinite supply elasticity. The price for these regions is fixed at a benchmark level. For the other regions, available irrigation water is treated as a fixed stock so endogenous price adjustments ensure market clearing. This option can be activated as an additional closure file, and the list of water stressed regions is found under “*scen\closures\water.gms*”.

3.9.2 GHG Emissions

GTAP offers data on emissions for carbon dioxide (CO2) and Non-CO2 as part of two different satellite accounts. The so-called GTAP-E database provides CO2 emissions data distinguished by fuel and by user for each of the 140 countries/regions in the GTAP9 Data Base. The GTAP-E database was already integrated into the data driver of CGEBox before the project started so the related emissions are integrated as equations in the modelling framework. This means that these emissions can be taxed, or the functioning of an emissions' rights market can be simulated, which affects the general equilibrium state.

The GTAP Non-CO2 Emissions database is now available, providing information on other greenhouse gas (GHG) emissions such as Methane (CH4), Nitrous Oxide (N2O), and Fluorinated gas (FGAS). These sources of climate relevant gases are of special interest for agriculture. Agricultural production activities account for a larger share of Methane emissions in many countries, linked to paddy rice production and enteric fermentation from ruminants while Nitrous Oxide is linked to the use of mineral and organic fertilizers. So far, the Non-CO2 emissions are only used for post-model reporting and have not been integrated in the equation system of the model yet. This means that endogenous or policy-driven variations in Non-CO2 emissions have no effect on the general equilibrium of the economy.

3.10 Trade in Value Added (TiVA)

The TiVA extension implements a well-established framework drawing on the Leontief multiplier analysis into the post-processing of CGEBox in order to assess the income-generating role of exports and to attribute sectoral outputs to final demand. Appendix A details how the TiVA extension, developed in the context of the project, is implemented in the GAMS code of CGEBox.

Trade has a dual role. First, it allows consumers to choose between domestically produced goods and imports; second, it offers income opportunities by means of exports. The first role is traditionally assessed in a CGE framework by reporting import shares on demand. The second role is reflected in the accounting identity for GDP by the difference between exports and import values, i.e. the balance of trade.

However, with the rapid increase in Global Value Chains (GVCs) and in intermediate trade flows, import shares, domestic and export shares are no longer a good indicator of the underlining sourcing. Domestic production comprises imported intermediates which generate income abroad. As a matter of fact, gross imports are not entirely foreign sourced and include some portion of domestic value added, which is imported back after further processing stages abroad (Daudin et al., 2011; Koopman et al., 2014). In the same way, export revenues comprise both domestic and foreign value added embedded in domestic and foreign intermediates.

The TiVA extension in the CGEBox introduces the decomposition of gross trade flows (as reported by standard trade statistics) in terms of value added content (for example, see Johnson and Noguera, 2012; Foster-McGregor and Stehrer, 2013; Wang et al., 2013; Koopman et al., 2014; Borin and Mancini, 2015). Specifically, it distinguishes between the domestic and the foreign value added. The domestic VA content of exports provides a measure of the contribution a given export makes to an economy's income, the remainder being the value of imported inputs representing the import content of exports or vertical specialization (Hummels et al., 2001). At sector level, it allows the value added originated in one (domestic or foreign) sector and exported by another sector to be calculated.

Finally, the decomposition of each sector's contribution to final demand facilitates the calculation of the output from each sector which is directly or indirectly (e.g., embedded as input in other intermediates used in the production of final goods) embedded in the final consumption.

The main indicators of the value added/output content of trade and final demand are summarized in Table 4. These are the first steps in modelling GVC-related trade and production within a CGE context and this framework is also forms the basis for a footprint analysis or for attributing environmental externalities linked to factor or output use to final demand. Further extensions would allow the foreign country of origin of value added in exports at the bilateral level to be disentangled, and the domestic and foreign portions of output for each sector to be distinguished.

Table 4: Indicators of Trade in Value Added in CGEBox

Indicator	Description
tradeInVaM	Value added multipliers
tradeInVa	Domestic and foreign value added content of trade
QTiva	Final demand decomposition in terms of sector contributions

Source: Authors' elaboration

4 Quantitative results

4.1 General considerations

The general impacts expected from reducing food waste in the European food industry are the following: as intermediate demand for primary agricultural products falls, supply and prices for agricultural products will decrease and, consequently, returns to agricultural primary factors will also fall, leading to loss of income for farmers. Reduced demand for land and irrigation water as well as less intensive agricultural production practices may lead to environmental quality improving. However, since the food industry needs other resources to reduce food waste, these could drive up the demand for such things as fossil fuel resources, with negative environmental impacts.

CGEs do not treat primary agricultural products as perfect substitutes, and the consequences vary in different regions/countries. One aim of reducing food waste is to increase food security. Food security is both a question of regional food availability and of being able to afford food, which depends on income and food prices. The impacts here are ambiguous. Dropping agricultural prices reduces the farmer’s income and therefore farmers' purchasing power but leads to cost savings in the Rest-of-the-World’s food industry, which should decrease the price of processed food. However, under the assumption that reducing food waste is not cost-neutral, European food processors will become less competitive so European net exports of processed food will decrease, countervailing the positive impact on global food security from reduced demand for agricultural products in Europe and cost savings in the Rest-of-the-World food industry.

4.2 Standard configuration

The reader is reminded that the so-called “Standard configuration” in CGEBox is not the Standard GTAP model but a rather complex configuration of CGEBox in which the MRIO and the Melitz model, GTAP-AEZ, GTAP-AGR with an agricultural and non-agricultural household, and the NUTS2 resolution for Europe are all combined (see Section 3).

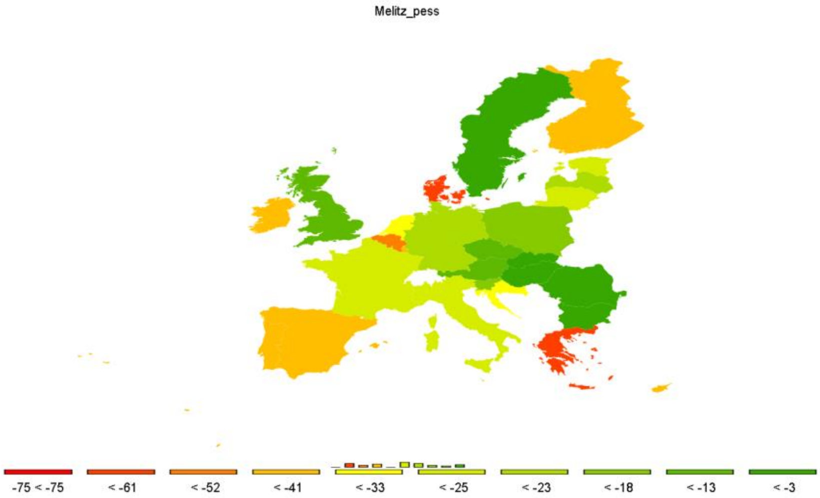
4.2.1 Welfare and income effects

At the global level, the impacts on agricultural prices of a cost-neutral 5% reduction in agricultural input of the European food industry (Cost Neutral Scenario) are very minor. That simply reflects the fact that the European food industry does not represent a large share of the global agricultural products demand. Global prices for primary agriculture products and food processing drop by -0.2% and -0.12% on average, respectively. However, the price drops are larger in the EU. For example, the drop for agricultural products is around -0.7% for crops and -2% for animals, respectively. Owing to stronger reliance on domestic products, the price per household in Sub-Saharan Africa shows a very small increase.

The price changes in the Europe Union differ between the Member States. Price drops can be as large as -4% across the EU. There is no single explanation of differences in price drops between Member States, which depend inter alia on the demand composition of the food industry and its sourcing from domestic and imports. Animal products have a tendency to show larger drops which reflects the fact that most slaughtering and meat processing is closer to the point of production compared to food processing of crops. This implies greater reliance on domestic output while exports of primary agricultural outputs play a very minor role in most cases, especially beyond (neighbouring) EU countries. This means that the domestic market of animal outputs has to absorb the reduction in input use by the food processing industry to a large extent.

As there are no significant differences between assuming that the food waste reduction is cost-neutral or not, results shown in this section refer to the more realistic case of only assuming non-cost neutral food waste reduction (Pessimistic Scenario). Global welfare drops very slightly with a purchasing power loss of around $0.1 USD per capita (measured by the equivalent variation). The welfare losses for EU Member countries would clearly be more pronounced compared to the world average. The EU average loss is around $25 USD per capita, with up to $75 USD per capita in Denmark, as illustrated in Figure 1. Larger changes are expected for Denmark, Greece, Ireland, the Netherlands, Belgium, Spain, and Portugal. For the countries experiencing larger losses, these are of the same magnitude as the EU budget contributions. It is worth recalling that the model provides an assessment of the cost implied by possible food waste reduction, but it does not evaluate all possible benefits associated with such a reduction, for example, reduced nitrogen and phosphorous loads.

Figure 1: Equivalent variation ($USD per capita)

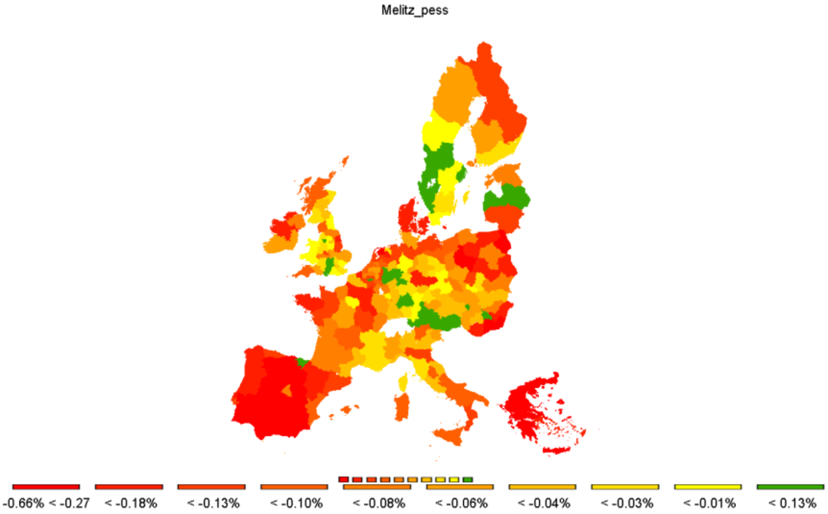


Source: Model results. Non-cost neutral (pessimistic) scenario

Figure 2 highlights that changes in value added would mostly affect the peripheral regions of the EU. While most regions are expected to be affected negatively, some are likely to experience a small but positive change, reaching 0.13% in a few regions. The few positive impacts disappear when only the impact on agricultural value added, of both crop and animal production, is focussed on. As shown in *Source:* Model results. Non-cost neutral (pessimistic) scenario

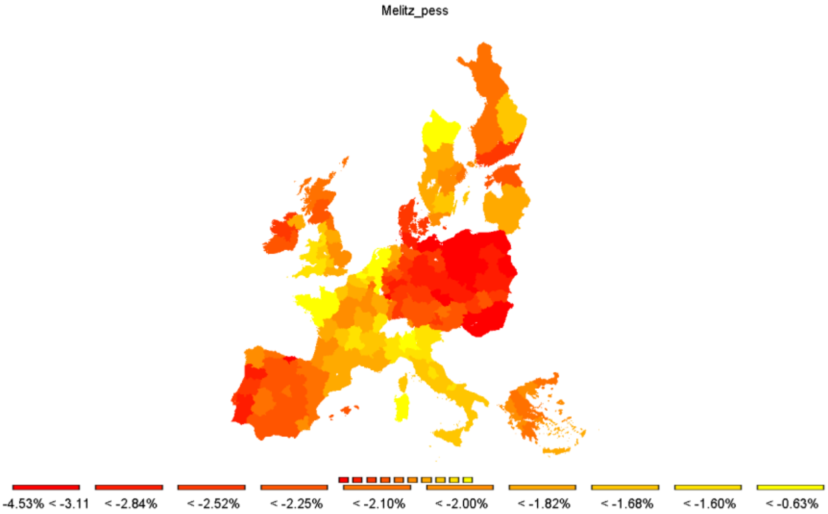
Figure 4, the largest decreases in the value added are forecast in the animal production sector, with a drop ranging from -2.5 up to -12.5% depending on the region. This reduction is due to the lower demand for inputs in the food sectors.

Figure 2: Change in value added at NUTS2 level



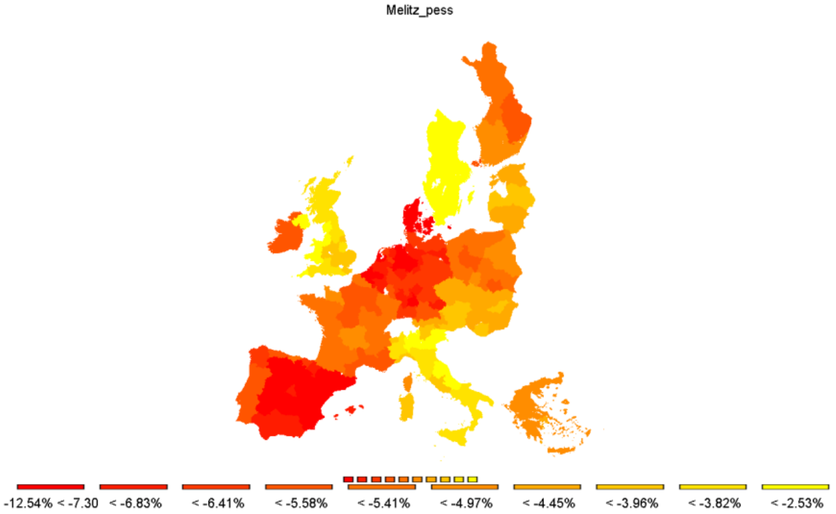
Source: Model results. Non-cost neutral (pessimistic) scenario

Figure 3: Change in value added for crop production



Source: Model results. Non-cost neutral (pessimistic) scenario

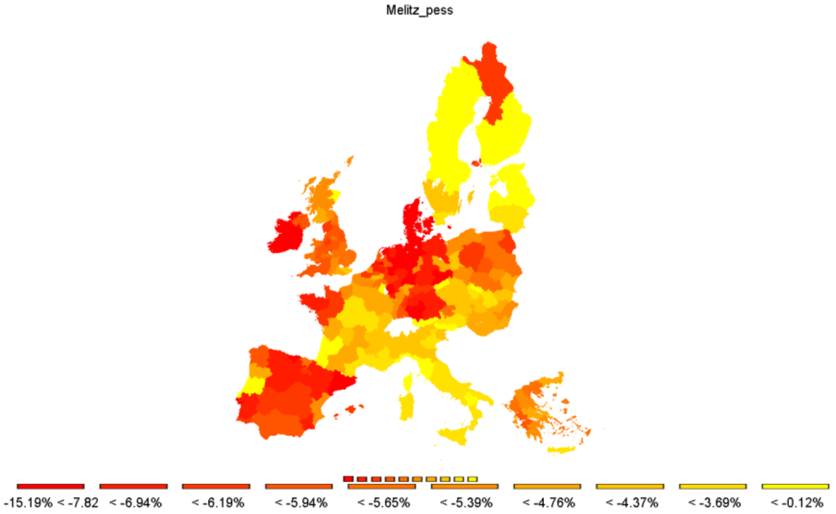
Figure 4: Change in value added for animal production



Source: Model results. Non-cost neutral (pessimistic) scenario

Figure 5 shows that land rents are likely to be negatively affected by food waste reduction, with large variability across the European regions from -0.1% in some regions of Finland, Sweden, Italy, and Southern France to -15% in several regions of Spain, Germany, Finland, and Ireland.

Figure 5: Change in agricultural land rents

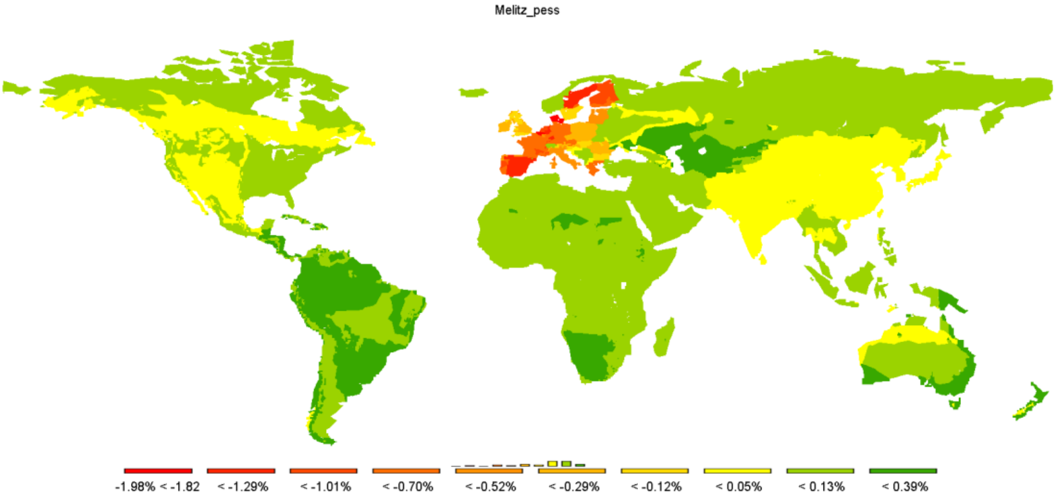


Source: Model results. Non-cost neutral (pessimistic) scenario

With respect to global CO2 emissions, no significant impact is foreseen because reduced methane emissions from less ruminant and raw production are offset by somewhat higher emissions from fossil fuel use. The impact is clearly larger in the EU and stronger if non-cost neutrality of reducing food waste is assumed. Under cost neutrality, the changes are all in the range of -0.1% to 0.1%. Under the more pessimistic assumptions, the largest reductions in emissions are observed in Lithuania (-0.49%), Finland (-0.25%), and France (-0.31%). In summary, reducing food waste in the EU might help the EU to somewhat reduce climate change impacts but any gain will be almost completely offset by leakage effects. Note that the CO2 accounting takes into consideration changes in carbon stocks related to land use change of managed areas.

As can be seen from **Figure 6**, the most obvious impact on global land use is a change in pasture land. Indeed, as the EU's ruminant production and output of red meat both drop, the rest-of-the world is expected to slightly expand its pastureland, with the largest increase being in South America and Africa.

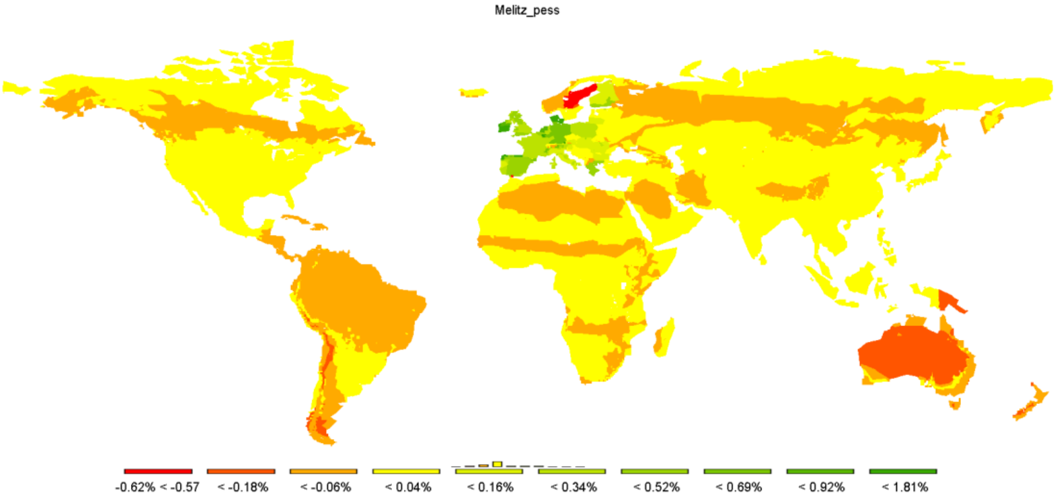
Figure 6: Change in pastureland cover



Source: Model results. Non-cost neutral (pessimistic) scenario

While croplands have a tendency to expand (see **Figure 7**), especially in the EU where drops in animal production are larger compared to the reductions in food production, in some regions such as Australia, but also parts of South America, the increase in pasture land may also reduce areas used for crop production.

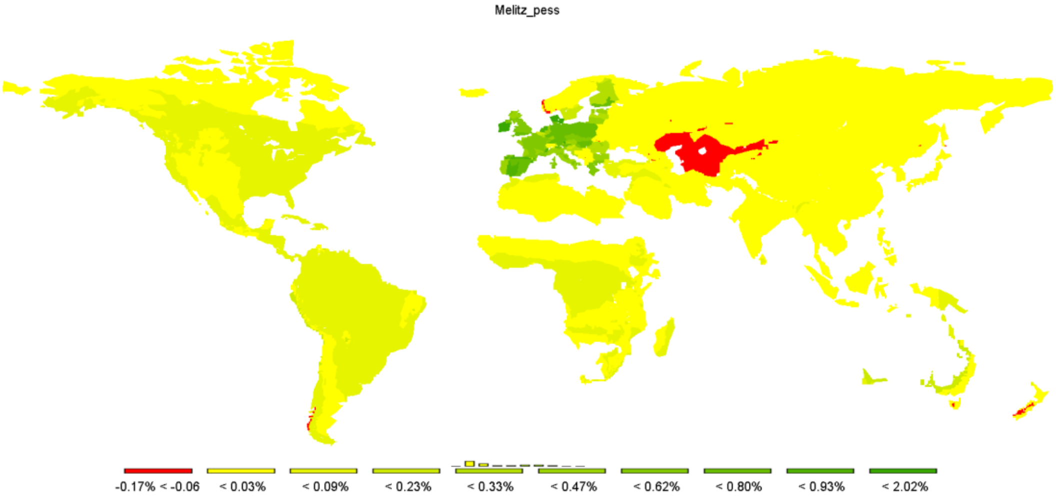
Figure 7: Change in cropland cover



Source: Model results. Non-cost neutral (pessimistic) scenario

Finally, he differentiated impact of a unilateral effort by the EU to reduce food waste can be clearly seen in the change in managed forest areas. Reduced demand for agricultural products in the EU releases pressure on crop and pasture land, which in the long run would lead to a certain extent of new afforestation. The opposite is true outside the EU, where pressure on the tropical rainforest would increase.

Figure 8: Change in managed forest land cover



Source: Model results. Non-cost neutral (pessimistic) scenario

The CGE modelling system does not (yet) track nitrate and phosphate balances as found in Multi-Commodity models, such as CAPRI. However, the reduced crop (-1%) and animal output per unit of land (-3%) found in the simulation shows an extensification effect, which can also be seen from the fact that total intermediate input use per unit of land drops by around -2% in crop and -4.3% in animal production.

4.3 Alternative model configurations

4.3.1 Trade specification

The following table shows the EV per capita results under different modelling options for international trade. As expected, the largest changes are in the Melitz extension. There is general agreement on the direction of the change, with only two exceptions. All configurations also show larger losses for Oceania, Spain, and Hungary. Interestingly, average changes for EU28 as a whole are rather limited, but differences between Member States are far larger. By way of example, despite the higher differences in the EV, simulated changes in land prices are rather similar for the various configurations of international trade.

Table 5: EV per capita under different trade configurations

	Melitz-MRIO	Melitz	ArmStd _CET	ArmStd
World	0.22	0.22	0.09	0.08
Australia, New Zealand	-1.59	-1.63	-2.09	-2.23
Rest of World	0.52	0.49	0.19	0.26
Middle East and Africa	0.15	0.16	0	0.06
Asia	0.02	0.02	0	0.01
America	-0.5	-0.47	-0.63	-0.67
EU28	3.16	312	2.46	2.13
Austria	8.84	9.21	5.58	5.54
Belgium	9.19	9.33	7.64	6.01
Germany	4.38	4.25	4.4	3.93
Czech Republic	-0.1	-0.1	1.27	0.66
Denmark	15.94	16.89	0.13	-0.85
Spain	-3.35	-3.28	-1.44	-1.62
Estonia	23.09	22.9	7.01	6.92
Finland	3.56	5.35	4.47	3.67
France	4	4.23	1.79	1.74
Greece	3.07	3.33	3.29	2.57
Hungary	-1.47	-0.99	-2.45	-3.15
Ireland	7.95	7.12	-4.19	-2.43
Italy	2.11	2.33	3.09	2.59
Netherlands	-5.3	-5.49	-7.85	-7.7
Poland	2.58	2.56	1.58	1.54
Portugal	-0.06	0.02	3.22	2.75
Sweden	3.4	3.51	3.7	3.38
United Kingdom	6.99	6.85	6.11	5.73
Bulgaria	-0.49	-0.55	-1.85	-1.82
Slovakia	2.21	2.69	1.86	1.56
Slovenia	4.59	3.75	1.32	1.33
Romania	6.54	6.49	4.04	3.77
Latvia	-1.87	-1.82	0.34	-0.12
Lithuania	0.42	0.33	-0.42	-0.62
Croatia	1.19	0.8	0.96	1.18
Rest of EU28	0.67	1.19	4.53	2.64

Source: Model Results. Non-cost neutral (pessimistic) scenario

As can be seen from Table 6 below, the difference between the Melitz and the Armington specifications can have significant impacts on results. The Armington formulation increases global trade significantly in relative terms, and almost all additional output is exported. In the Melitz model, increasing demand implies two opposing effects: distributing the fixed trade costs on larger quantities, which decreases costs, and letting less competitive firms enter the market, which increases costs. The net effect here is to reduce the increase in trade.

Interestingly, there is an increase in the global demand for food-processing products under the Armington configuration and the scenario where cost-neutrality at benchmark prices is assumed. As prices for agricultural inputs drop due to the assumed reduction in input demand per unit of output in the food industry, the food industry becomes more competitive and increases its output. Note that this implies a contribution to global food security as even in many developing countries the main staple foods such as bread stem from food processing.

Table 6: Global demand for food-processing products

	ArmStd	ArmStd CET	Melitz	Melitz MRIO
Total	12312	12312	12123	12122
	1.69%	1.70%	0.13%	0.13%
Domestic	10637	10637	10645	10644
	0.05%	0.05%	0.13%	0.12%
Imported	1675	1675	1478	1478
	13.54%	13.56%	0.19%	0.17%

Source: Model Results. Non-cost neutral (pessimistic) scenario

4.3.2 Trade in value added

The TiVA extension allows some interesting additional results to be obtained. As previously mentioned, food waste reduction leads to a reduction in EU food-processing output largely because of the contraction in exports. The demand for crops and animal agricultural inputs from the food sector decreases accordingly.

Looking at the demand side, Table 7 presents the change of the agricultural inputs embedded in final consumption of food products for different markets in the pessimistic scenario. The reduction differs from the 5% reduction in domestic agricultural inputs used by the EU food industry simulated for two reasons. Since calculations are based on global Leontief multipliers, they take into account both domestic and imported agricultural inputs as well as agricultural inputs embedded in intermediate goods produced by other sectors and used in food production. Even in the case of the EU, i.e., the region directly hit by the shock, the reduction in the value output from crops and animals is less than 5% (-2.12% and -1.70%, respectively). However, there are large differences across the Member States: reductions in Belgium exceed 4% while in Greece they are less than 1%.

Table 7: Primary agricultural output embedded in the final consumption of food products

	Crops		Animals	
World	900.86	-0.25%	622.06	-0.57%
Australia, New Zealand	5.03	-0.07%	8.46	-0.21%
Rest of World	33.64	0.28%	31.67	0.14%
Middle East and Africa	97.76	-0.01%	70.66	-0.17%
Asia	483.38	-0.03%	184.20	-0.35%
America	183.84	-0.08%	206.23	-0.36%
EU28	97.20	-2.12%	120.83	-1.70%
Austria	1.37	-1.98%	1.71	-1.14%
Belgium	2.67	-4.02%	1.39	-4.42%
Germany	23.91	-2.03%	20.34	-1,00%
Czech Republic	1.90	-2.38%	1.53	-1.50%
Denmark	0.93	-1.77%	1.21	-3.14%
Spain	11.97	-2.09%	13.45	-1.83%
Estonia	0.08	-3.35%	0.16	-3.40%
Finland	0.65	-2.40%	1.57	-2.92%
France	11.29	-2.38%	17.47	-2.95%
Greece	3.70	-0.93%	4.13	-0.65%
Hungary	1.44	-1.88%	2.53	-0.63%
Ireland	0.60	-1.71%	1.30	-1.09%
Italy	11.28	-2.01%	16.08	-1.77%
Netherlands	1.71	-2.31%	3.94	-2.50%
Poland	4.89	-1.70%	8.60	-2.22%
Portugal	1.94	-2.72%	2.37	-2.57%
Sweden	1.33	-2.30%	1.91	-1.27%
United Kingdom	9.15	-1.72%	14.28	0.01%
Bulgaria	0.43	-2.67%	0.62	-2.22%
Slovakia	0.54	-2.73%	1.01	-1.95%
Slovenia	0.12	-1.13%	0.29	-2.28%
Romania	3.70	-2.93%	2.12	-2.41%
Latvia	0.26	-1.36%	0.24	-2.77%
Lithuania	0.50	-2.75%	0.72	-2.74%
Croatia	0.64	-2.47%	1.08	-3.02%
Rest of EU28	0.20	-2.66%	0.77	-4.87%

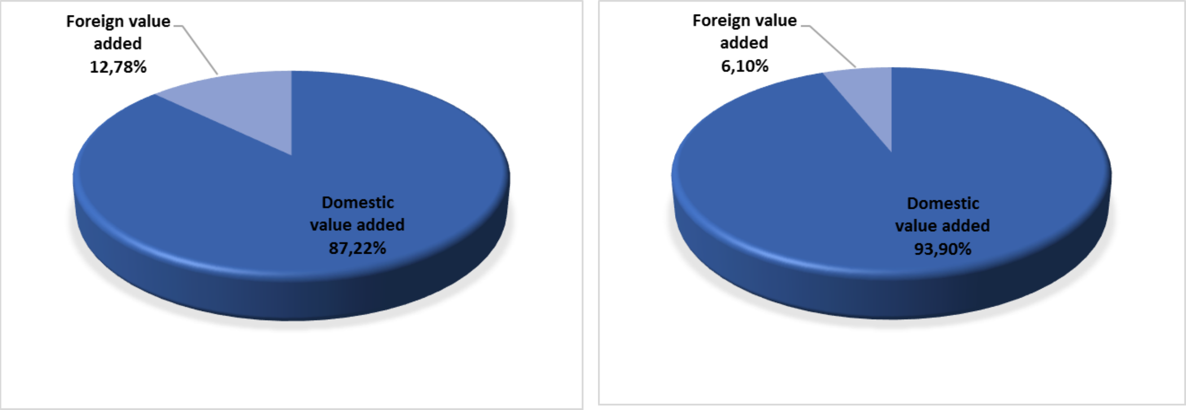
Source: Model Results. Non-cost neutral (pessimistic) scenario

The reduction in domestic agricultural inputs demand by the food sector in several EU countries is compensated by foreign agricultural goods and by intermediates provided by other sectors that also need agricultural inputs. Due to the shock, production of food exports would require more inputs from other sectors of the economy (e.g., services and industry) which would increase their output and, consequently, their intermediate demand of those primary agricultural inputs which are cheaper due to the contraction of demand from the food industry.

The TIVA indicator is used to compute the domestic and foreign content for each intermediate input in the production of processed-food exports. The impact of the food waste reduction on agriculture and food exports is assessed by considering: i) the domestic content of EU exports; ii) the EU's direct exports (value added originating in the domestic sector which is exported through the same sector's exports; and iii) the EU's indirect exports (value added originating in the domestic sector and embedded in the exports of another domestic sector).

Figure 9 shows that crop exports have the highest domestic value-added share (greater than 90%). The EU's exports of food and animal products are more reliant on foreign inputs which represent around 12% of the total exported value.

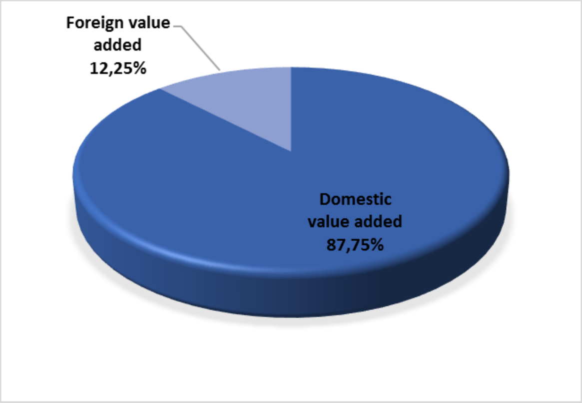
Figure 9: The composition of the EU's exports in food and agricultural products (shares in gross exports)



a) Food processing

b) Crops

c) Animals



Source: Model Results. Baseline

It is worth emphasizing that EU agricultural value added is also exported through food exports. The value of domestic intermediate goods provided by different sectors is presented in Table 8.

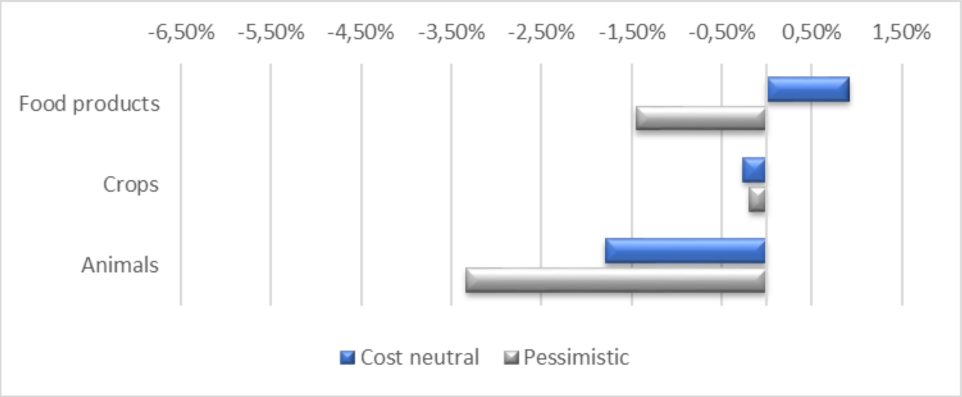
Table 8: Decomposition by sector of the domestic value added in food-processing exports (million USD)

Sector of origin of value added	
Food processing	193.61
Crops	16.87
Animals	24.46
Mining and Extraction	2.64
Electric power sources	4.9
Industry	24.52
Services	66.24
Other	6.09
Total	339.33

Source: Model Results. Baseline

We find very different impacts under the two simulated assumptions, which lead us to consider the results here for both scenarios. Figure 10 shows the impacts on the domestic value added embedded in exports of processed food and primary products. Under the pessimistic scenario, European exports of food products decrease as a result of the decrease in competition. Such a reduction would carry through the crop and animal sectors, though with a much smaller impact on the former. Interestingly, the cost neutral scenario would lead to an increase in exported values but in this case the positive impact does not carry through the primary sectors.

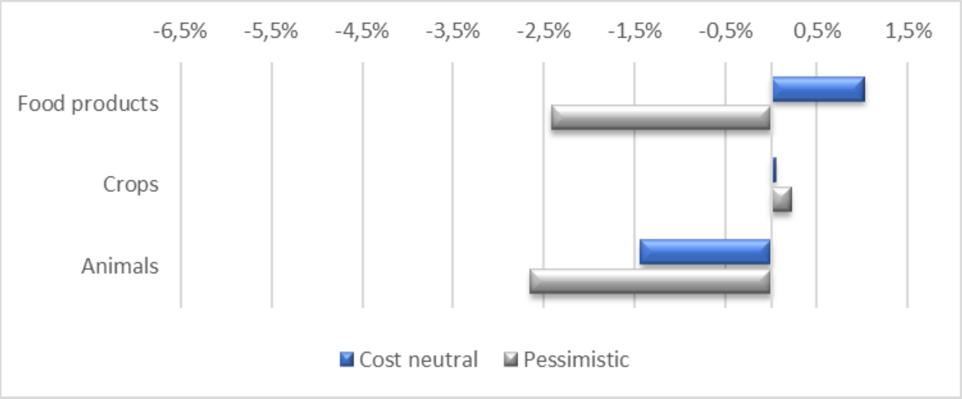
Figure 10: Impact by sector on the domestic value added in the EU's total exports (% change)



Source: Model Results. Scenarios

Next, we consider the impact on direct export, that is, the change in the exported domestic value-added originating in the exporting sector (Figure 11). In other words, we net the results presented in Figure 10 from the values for domestic intermediates.

Figure 11: Impact by sector on the direct domestic value added in the EU's exports, (% change)

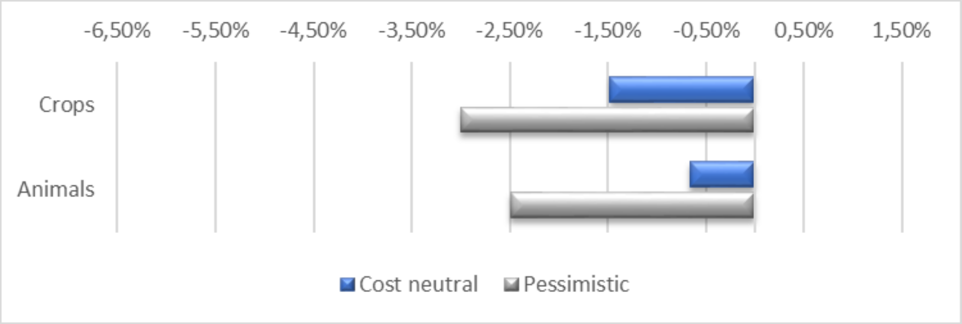


Source: Model Results. Scenarios

In the cost neutral scenario, there is not a significant change for the food sector while Animals would record a smaller reduction, and Crops would even record a small increase. The same is true for the agricultural sectors in the pessimistic scenario. However, in this scenario the direct value added exported by the food sector would record a larger reduction.

Finally, Figure 12 shows the impact of the two scenarios on the demand for EU agriculture by the food sector. It is worth noting that the reduction would be larger in the crop sector compared to the animal sector, a somewhat surprising result given the results presented in Table 8. More importantly, a reduction is recorded in the use of EU agricultural inputs even in the cost-neutral scenario that leads to an increase in food exports.

Figure 12: Impact of primary inputs in the EU's exports of food products on the domestic value added (% change)



Source: Model Results. Scenarios

4.3.3 Production Function Nesting

The chosen configuration introduces several differences to the GTAP Standard model. Most importantly, all intermediate inputs can be substituted against each other. In order to test if the results are robust for various key assumptions used in the chosen configuration, we compare several core results against a version which uses neither GTAP-AGR nor GTAP-E. This should particularly reduce the substitution between agricultural feedstocks in the food processing industry which is a key aspect of the study. The overall impact on GDP is negligible, with maximal changes at country level being 0.03% when using the pessimistic scenario as the test case. Changes in CO2 emissions are somewhat more dependent on the chosen configuration: reducing substitution possibilities can drive up emissions (+13% in Finland) or reduce them (-0.50% in Ireland). The impact on CO2 emissions at global level is virtually zero and very small at EU aggregate level, being -0.05%.

Impacts on agricultural household income, which mostly depends on factor income earned in the agricultural sector, are more pronounced. In Denmark (-1.1%), Ireland (-0.85%), Germany (-0.57%), and The Netherlands (-0.54%) farm income drops by more than half a percent in the version without GTAP-AGRI and GTAP-E compared to the default configuration used in the model. Sizeable positive changes are not found, the maximum is an increase of 0.18% in the Rest of World; all EU Member countries, with the exemption of Finland (+0.01%), show a drop in agricultural income under the simpler model configuration. This is explained by the fact that return to land seems to consistently drop more in all EU Member countries.

A driver behind these results is the fact that reduced flexibility in allocating agricultural output and energy use in demand leads to a larger drop in agricultural outputs in the EU: crop and animal output respectively fall by -0.5% and -0.23%, compared to the standard configuration used in the study. At the global level, the food industry slightly reduces its use of agricultural inputs per unit of output compared to the standard configuration. This result mainly stems from the EU, where animal outputs per unit of output in food processing drop by -0.25% (only -0.11% for crops).

Overall, the examples of changes discussed above underline that a more realistic depiction of substitution possibilities in the use of agricultural output can indeed have some impacts on the margin in simulated results.

4.3.4 Modelling natural resources

Modelling natural resources in a more refined way compared to the GTAP standard model is based on the chosen configuration according to the interaction of several modules. Firstly, deriving the SAM from the GTAP-Water version treats irrigation water in agriculture as a separate factor and differentiates between irrigated and non-irrigated crops.

Secondly, the GTAP-AEZ module informs the model about physical land and introduces differentiation by region between different Agro-Ecological Zones (AEZs). Land is not mobile across AEZs, decreasing factor mobility for land. In each AEZ, CET nests distribute total managed land to crop land, pasture land, and managed forests, the assumed transformation elasticities are lower compared to what is assumed for land at national level across all uses in the GTAP standard model. Furthermore, a CET is used inside crop land to distribute crop land to the various crops. Overall, the AEZ module should reduce land mobility and so lead to lower substitutions between activities using land and larger changes in land rents.

Thirdly, here the CO2 and non-CO2 extensions are only used in the post-model processing and so do not impact on simulation behaviour. The relevant findings are reported in the previous Sections.

4.3.5 Without NUTS2

Running the standard configuration used in the study without the NUTS2 resolution seems to have limited impact on the macro-results. The differences in real GDP for the EU countries are less than 0.3%. As expected, differences are more pronounced in the food processing sector where the shock is implemented. These differences reflect the fact that the NUTS2 module reduces factor mobility in the EU countries, compared to a version where all factor markets are national, especially for irrigation water and land which are considered to be non-mobile across regions. Mobility is also reduced because additional CET-nests distribute mobile or sluggish factors from a national pool to the regions.

At the EU28 level, the full model predicts a slight reduction in food processing output by -0.07% whereas the same configuration without the NUTS2 extension forecasts an increase of 0.34%. A lower increase or a sharper decrease, or a reduction instead of an increase, is found for all Member States in the version with the NUTS2 extensions compared to the version only modelling nations. Differences in total global CO2 emissions as an important externality are however negligible.

While using the NUTS2 extension clearly drives up solution time due to the larger model size, it seems to provide robust results. As such, its use can probably be recommended for all applications where (selected) NUTS2 results are of interest.

5 Conclusion

The project has three major aims: (1) to analyse the impacts of EU efforts to curb food waste, (2) to test the CGEBox modelling system under policy relevant shocks and (3) to improve CGEBox in selected areas.

Contrary to the other studies, it is not assumed here that a larger reduction of food loss and waste is costless. Rather, two options are analysed: the first assumes cost-neutrality at benchmark prices, whereas the second one assumes that reducing food waste would incur additional costs. Food waste is assumed to be reduced in the food industry only, and not by final demanders.

A unilateral commitment of the EU to reduce food loss and waste would most likely decrease the competitiveness of the EU food processing. Reduced demand for primary agricultural inputs would shrink the EU's agricultural sectors, pressuring on farm incomes and land prices. The contribution to global food security would be very minor, as the adjustments would be concentrated in EU market. Rather, as many developing countries are importers of both primary agricultural products and of processed food, increasing global prices for processed food would harm them.

We could not find any significant impact on emissions relevant for climate change at global level and only very limited contribution inside the EU.

With regard to testing CGEBox, the modelling systems showed its usefulness, especially with regard to depicting outcomes at NUTS2 level and in quantifying global land use impacts, based on GTAP-AEZ, while differentiating between irrigated and non-irrigated crops. It was possible to maintain the full sectoral detail for agri-food as found in the GTAP data base, despite the fact that all EU 28 Member countries were considered by the analysis and a complex model configuration used. The application of the Melitz module provides new insights about international trade, by considering the impact of sector-wide and trade-link specific fixed costs, firm productivity distribution and love of variety. CGEBox thus seems an interesting complement to other models used for policy impact assessment; its modular and flexible concept renders it quite versatile.

During the project's lifetime, the modelling system was improved in several aspects. The TiVA part was completely re-factored, and it is now based on the global Leontief inverse and allows attributing production by trading partner to final demand, as well as CO2 emissions. The NUTS2 layer was informed by data on regional irrigated areas and a differentiation between water- and non-water stressed regions was introduced.

It was already noticed, in the introductory section, that there is no universal consensus on the definition of "food waste" and that the concept may have alternative interpretations. Therefore, in order to assess the significance and implications of the numerical results obtained, it is essential to understand how "food waste" has been interpreted here, and how the concept has been technically implemented into the mathematical model.

The overall approach followed in this work is the one typical of mainstream economics, which posits assumptions about preferences and rationality. First, we have refrained from making any normative or "pedagogical" consideration about individual or social preferences. This contrasts with the implicit moral judgement associated with the word "waste", recalling not only inefficiency, but also injustice and deprecated behaviour. Second, rationality as assumed in model construction implies that the observed food waste is the outcome of voluntary choices considered optimal by the individual making that choice. In other words, observed waste must be, economically speaking, efficient by construction. As a corollary: any departure from an optimal state must be costly, at least in the aggregate.

Actually, it could well be possible that individual choices may not be socially optimal, but this possibility has not been explored in this research, and for good reasons. This may happen whenever social values do not coincide with private ones, so that externalities and market failures emerge. For instance, suppose that consumers only want perfectly rounded and red apples. You may say that discarding "imperfect" yet fully eatable apples is a "waste". But, from a scientifically neutral perspective, we do not want to discuss why consumers have such preferences. Rather, the right questions to pose are: is there a socially valuable use of "imperfect apples"? Why apple producers choose to discard them? What kind of economic incentives can be offered to realign individual behaviour with social objectives?

Coming more specifically to the numerical exercise illustrated in this report, it should be noticed that a strategy of reduction of food waste has been interpreted here as a change in the production technology of the food processing industry (in Europe). This change in technology takes place by reducing the inputs of agricultural goods into food processing, while scaling up the usage of all other production factors (in a cost neutral or in a cost increasing way). Therefore, we have simulated an improved efficiency in the utilization of agricultural goods, compensated by higher employment of all other factors.

This compensation mechanism deserves some discussion. First, suppose that no such compensatory change occurs. In this case, the reduction of food waste in the processing industry would be a pure efficiency gain. This means that you could produce more with the same resources, or that you would need fewer resources to get the same output. But if that gain can be easily grasped, why has it not yet been obtained? Agents cannot be rational, profit-maximizers and at the same time selecting the "wrong" technology which is wasting inputs.

If we exclude that "manna from heaven" case, then there must be some implementation costs. Which costs? Here, it is difficult to make any valuation without specifying in detail which measures would be taken to reduce the gross amount of agricultural inputs utilized. Remember that the model employed here is a macroeconomic one, meaning that behind industries and households there are millions of individuals and firms. As a consequence, there is no practical way to get any realistic estimate of implementation costs for waste reduction programs (disaggregated by industrial category). Perhaps some useful information could be obtained by interfacing the CGE model with a microsimulation one, but this would go beyond the scope of this work. Therefore, the chosen solution has been the one of a proportional scaling of other production factors, which may not be very realistic but has at least the merit of not introducing additional and somehow arbitrary distortions in the simulation experiments.

It may be worthwhile making a distinction between fixed and variable implementation costs. The costs considered so far are variable, because it is assumed that the food processing sector keeps using more non-agricultural inputs as long as food waste is contained. There may be cases, however, where efficiency improvements (in this case, in the utilization of agricultural inputs), are made possible by specific investments (e.g. the realization of better food storage facilities). Considering investment-driven improvements adds a time dimension to the problem, whereby at least two phases should be kept distinct: one phase of investment, and one phase of productivity benefits.

One could also notice that this research has focused on the food processing industry alone, which account for a large share of food waste, but not the largest one (which occurs at the final consumption stage; see, e.g., Monier et al. (2010), Stenmarck, Jensen, and Quested (2016)). Although one study on food waste at the household level does exist (for the Netherlands, Britz, Dudu and Ferrari (2014)) the point we want to make here is that most of the methodology and approach followed in this study would apply equally well to final consumption in the household.

Indeed, a representative, aggregate household can be conceived as a sort of special industry, which “produces” utility, using consumption goods and services. Improvements in “consumption productivity” would then mean that you could be as happy as before, or even happier, while consuming lower amounts of food. On the other hand, the savings obtained by purchasing less food could allow getting higher amounts of other consumption items.

In the same vein, the distinction between variable and fixed costs applies to the household sector as well. A case, which is especially interesting in this context, is when investments in food waste reduction have a public good nature. A public good is a good where consumption by one agent does not exclude consumption by other agents and, for this reason, it should be provided by the public sector. A typical instance of public good is information. For example, in the context of food waste reduction, we could envisage a public information campaign, capable of permanently reduce food waste by final consumers.

To summarize, the modelling exercise presented in this study has its own limitations and cannot address all the many facets of the food waste phenomenon. Other aspects have been briefly discussed in this section. It turns out that much of the qualitative insights obtained in our numerical exercise should carry over to more complex and comprehensive analyses. If the existence of market failures and public goods would be brought into the picture, more scope for policy intervention would emerge and aggregate welfare effects would be somewhat more on the positive side.

References

Akgul, Z., Villoria, N. B., & Hertel, T. W. (2016). GTAP-HET: Introducing firm heterogeneity into the GTAP model. *Journal of Global Economic Analysis*, *1*(1), 111-180.

Alexander, P., Brown, C., Arneth, A., & Finnigan, J. (2017). Losses, inefficiencies and waste in the global food system. *Agricultural Systems*, 153, 190-200.

Bagherzadeh, M., Inamura, M., & Jeong, H. (2014). Food Waste Along the Food Chain, OECD Food, Agriculture and Fisheries Papers, 71. Paris: OECD Publishing.

Banse, M., Van Meijl, H., Tabeau, A., Woltjer, G., Hellmann, F., & Verburg, P. H. (2011). Impact of EU biofuel policies on world agricultural production and land use. *Biomass and Bioenergy*, *35*(6), 2385-2390. 1

Beretta, C., Stoessel, F., Baier, U., & Hellweg, S. (2013). Quantifying food losses and the potential for reduction in Switzerland. Waste Management, 33, 764-773.

Betz, A., Buchli, J., Göbel, C., & Müller, C. (2015). Food waste in the Swiss food service industry – Magnitude and potential for reduction. Waste Management, 218-226.

Barilla Centre for Food and Nutrition (BCFN). (2012). Food waste: causes, impacts and proposals. Parma: Barilla Center for Food and Nutrition.

Borin, A., & Mancini, M. (2015). Follow the Value Added: Bilateral Gross Export Accounting. Temi di Discussione (Working Papers), 1026. Rome: Banca d'Italia.

Bräutigam, K.-R., Jörissen, J., & Priefer, C. (2014). The extent of food waste generation across EU-27: Different calculation methods and the reliability of their results. Waste Management & Research, 32(8), 683-694.

Britz, W. (2012). RegCgeEU+ in GAMS, documentation including the Graphical User Interface. *CAPPRI-RD Deliverable*, *3*(4).

Britz, W. (2014). A New Graphical User Interface Generator for Economic Models and its Comparison to Existing Approaches. *German Journal of Agricultural Economcis*, *63*(4)

Britz, W., & van der Mensbrugghe, D. (2016). Reducing unwanted consequences of aggregation in large-scale economic models-A systematic empirical evaluation with the GTAP model. *Economic Modelling*, *59*, 463-472

Britz, W., & Witzke, P. (2012). CAPRI model documentation 2012. *Verfügbar unter: www. capri-model. Org*

Britz, W., Dudu, H., & Ferrari, E. (2014). Economy-wide impacts of food waste reduction: a general equilibrium approach. In *presentation at the EAAE 2014 Congress 'Agri-Food and Rural Innovations for Healthier Societies' August,* 26.

BSR. (2014). Analysis of U.S. Food Waste Among Food Manufacturers, Retailers, and Restaurants.. Food Marketing Institute.

Buzby, J. C., & Hyman, J. (2012). Total and per capita value of food loss in the United States. Food Policy, 37, 561-570.

Caldeira, C., Corrado, S., & Sala, S. (2017). Food Waste Accounting - Methodologies, challenges and opportunities, EUR 28988 EN, JRC109202.. Luxembourg(Luxemburg): Publications Office of the European Union.

Calzadilla A., Rehdanz, K., Roson, R., Sartori, M., & Tol, R. (2016). Review of CGE Models of Water Issues, in: A. Dinar (ed.) The WSPC Reference on Natural Resources and Environmental Policy in an Era of Global Change, Volume 3, T. Byant (ed.) Global Economic Models – CGE, World Scientific Publishing, 2016.

Campoy - Munoz, P., Cardenetea, M., & Delgado, M. (2017). Economic impact assessment of food waste reduction on European countries through social accounting matrices. Resources, Conservation and Recycling, 122, 202-209.

Chaboud, G., & Daviron, B. (2017). Food losses and waste: Navigating the inconsistencies. Global Food Security, 1-7.

Daudin, G., Rifflart, C. & Schweisguth, D. (2011). Who Produces for Whom in the World Economy? *Canadian Journal of Economics*, 44(4), 1403-1434.

Davis, G. C., & You, W. (2013). Estimates of returns to scale, elasticity of substitution, and the thrifty food plan meal poverty rate from a direct household meal production function. Food Policy, 43, 204-212.

Ellison, B., & Lusk, J. L. (2016). Examining Household Food Waste Decisions: A Vignette Approach. 2016 Agricultural and Applied Economics Association, Boston, MA, July 31 – August 2. Boston, MA.

Engström, R., & Carlsson-Kanyama, A. (2004). Food losses in food service institutions Examples from Sweden. Food Policy, 29, 203-213.

European Commission. (2011). Roadmap to a Resource Efficient Europe, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, COM(2011)571,. Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52011DC0571.

European Commission. (2014). Impact assessment on measures addressing food waste to complete SWD (2014) 207 regarding the review of EU waste management targets, Commission Staff Working Paper: SWD(2014) 289. Brussels: European Commission..

European Commission. (2015). Proposal for a directive of the European Parliement and of the Council amending Directive 2008/98/EC on waste, COM(2015)0595. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52015PC0595.

European Council. (2016). Council conclusions on food losses and food waste, 10730/16,. Retrieved from http://data.consilium.europa.eu/doc/document/ST-10730-2016-INIT/en/pdf.

European Parliament. (2018). Position of the European Parliament adopted at first reading on 18 April 2018 with a view to the adoption of Directive (EU) …/… of the European Parliament and of the Council amending Directive 2008/98/EC on waste, P8_TC1-COD(2015)0275,. Retrieved 04 23, 2018, from http://www.europarl.europa.eu/sides/getDoc.do?type=TA&reference=P8-TA-2018-0114&language=EN&ring=A8-2017-0034#BKMD-11.

FAO. (2011). Global food losses and food waste – Extent, causes and prevention. Rome: FAO.

FAO. (2012). Food wastage footprint. An environmental accounting of food loss and waste. Concept Note. Retrieved from Food wastage footprint. An environmental accounting of food loss and waste.

FAO. (2013). Food wastage footprint: Impacts on natural resources. Rome: FAO.

FAO. (2014a). State of Food Insecurity in the World. Retrieved from http://www.fao.org/3/a-i4030e.pdf.

FAO. (2014b). Definitional framework of food loss. Rome: FAO.

FAO. (2014c). Mitigation of food wastage societal costs and benefits.. Rome: FAO.

FAO. (2014d). Food loss assessments: causes and solutions Case Studies in Small-scale Agriculture and Fisheries Subsectors. Rome: FAO.

FAO. (2014d). Food wastage foorprint: Full-cost accounting. Rome: FAO.

Filho, W. L., & Kovaleva, M. (2015). Food Waste and Sustainable Food Waste Management in the Baltic Sea Region. New York: Springer.

Foster - McGregor, N., & Stehrer, R. (2013). Value Added Content of Trade: A Comprehensive Approach. *Economics Letters*, 120(2), 354-357.

Gjerris, M., & Gaiani, S. (2013). Household food waste in Nordic countries: Estimations and ethical implications. Etikk i praksis. Nordic Journal of Applied Ethics, 7(1), 6-23.

Gjerris, M., & Gaiani, S. (2013). Household food waste in Nordic countries: Estimations and ethical implications. Etikk i praksis. Nordic Journal of Applied Ethics, 7(1), 6-23.

Gooch, M., Felfel, A., & Marenick, N. (2010). Food Waste in Canada. Retrieved 10 10, 2017, from Value Chain Management Centre: https://vcm-international.com/wp-content/uploads/2014/01/Food-Waste-in-Canada-November-2010.pdf.

Hall, K. D., Guo, J., Dore, M., & Chow, C. C. (2009). The Progressive Increase of Food Waste in America and Its Environmental Impact. Plos ONE, 4(11), 1-6.

Haqiqi, I., Taheripour, F., Liu, J., & van der Mensbrugghe, D. (2016). Introducing Irrigation Water into GTAP Data Base Version 9. Journal of Global Economic Analysis, 1(2), 116-155; data can be downloaded from https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=5168.

HLPE. (2014). Food losses and waste in the context of sustainable food systems. Rome: High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security.

Höjgård, S., Jansson, T., & Rabinowicz, E. (2013). Food waste among Swedish households much ado about nothing?, Working Paper No: 2013:8. Agrifood Economics Center.

Horridge, M., & Pearson, K., (2011). Solution Software for CGE Modeling. COPS General Paper No. G-214.

Jafari, Y. and Britz, W. (2018), Modelling heterogeneous firms and non-tariff measures in Free Trade Agreements using Computable General Equilibrium, Economic Modelling, accepted.

Johnson, R.C. & Noguera, G. (2012). Accounting for intermediates: Production sharing and trade in value added. *Journal of International Economics*, 86(2), 224–236.

Jörissen, J., Priefer, C., & Bräutigam, K.-R. (2015). Food Waste Generation at Household Level: Results of a Survey among Employees of Two European Research Centers in Italy and Germany. Sustainability, 7, 2695-2715.

Ju, M., Osako, M., & Harashina, S. (2017). Food loss rate in food supply chain using material flow analysis. Waste Management, 61, 443-454.

Katajajuuri, J.-M., Silvennoinen, K., Hartikainen, H., & Heikkilä, L. (2014). Food waste in the Finnish food chain. Journal of Cleaner Production, 73, 322-329.

Kibler, K. M., Reinhart, D., Hawkins, C., Motlagh, A. M., & Wright, J. (2018). Food waste and the food-energy-water nexus: A review of food waste management alternatives. Waste Management, 74, 52-62.

Koester, U. (2014). Food Loss and Waste as an Economic and Policy Problem. Intereconomics - Review of European Economic Policy, 49(6), 348-354.

Koivupuro, H.-K., Hartikainen, H., Silvennoinen, K., Katajajuuri, J.-M., Heikintalo, N., Reinikainen, A., et al. (2012). Influence of socio-demographical, behavioural and attitudinal factors on the amount of avoidable food waste generated in Finnish households. International Journal of Consumer Studies, 36, 183-191.

Koopman, R., Wang, Z., & Wei, S. (2014). Tracing Value-Added and Double Counting in Gross Exports. *American Economic Review*, 104(2), 459-494.

Krugman, P. (1991). Increasing returns and economic geography. Journal of Political Economy, 99(3), 483–499

Kummu, M., Moel, H. d., Porkka, M., Siebert, S., Varis, O., & Ward, P. (2012). Lost food, wasted resources: Global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use. Science of the Total Environment, 438, 477–489.

Lipinski, B., Hanson, C., Waite, R., Searchinger, T., Lomax, J., & Kitinoja, L. (2013). Reducing Food Loss and Waste. Retrieved from http://www.wri.org/publication/reducing-food-loss-and-waste.

Mercenier, J., Brandsma, A., Di Comite, F., Diukanova, O., Lecca, P., LÃ³pez-Cobo, M.,... & Torfs, W. (2016). *RHOMOLO-v2 Model Description: A spatial computable general equilibrium model for EU regions and sectors* (No. JRC100011). Joint Research Centre (Seville site).

Monier, V., Shailendra, M., Escalon, V., O’Connor, C., Gibon, T., Anderson, G., et al. (2010). Preparatory Study on Food Waste across EU 27: Final Report. Brussels: European Commission (DG ENV) Directorate C-Industry.

Munesue, Y., Masui, T., & Fushima, T. (2015). The effects of reducing food losses and food waste on global food insecurity, natural resources, and greenhouse gas emissions. Environmental Economics and Policy Studies, 17(1), 43-77.

O'Donovan, R. (2018, 04 16). AGRAFACTS. No.31-18. Brussels: AGRA-EUROPE.

OECD. (2014, 07 1). OECD.Stat. Retrieved 24 4, 2018, from Food Waste: https://stats.oecd.org/Index.aspx?DataSetCode=FOOD_WASTE.

Parizeau, K., Massow, M. v., & Martin, R. (2015). Household-level dynamics of food waste production and related beliefs, attitudes, and behaviours in Guelph, Ontario. Waste Management, 35, 207-217.

Planchenstainer, F. (2013). Food Surplus as an Opportunity and Its Legal Incentives, The Trento Law and Technology Research Group Research Paper, 13.

Pretty, J. (2005). Farm costs and food miles: an assessment of the full cost of the UK weekly food basket. Food Policy, 30, 1-19.

Priefer, C., Jörissen, J., & Bräutigam, K.-R. (2013). Technology options for feeding 10 billion people: Options for Cutting Food Waste, IP/A/STOA/FWC/2008-096/Lot7/C1/SC2 -SC4. Luxemburg: European Parliament.

Reutter, B., Lant, P. A., & Lane, J. L. (2017). The challenge of characterising food waste at a national level—An Australian example. Environmental Science and Policy, 78, 157-166.

Rutherford, T. F., & Törmä, H. (2010). Efficiency of fiscal measures in preventing out-migration from North Finland. *Regional Studies*, *44*(4), 465-475.

Rutten, M. M. (2013). What economic theory tells us about the impacts of reducing food losses and/or waste:implications for research, policy and practice. Agriculture & Food Security, 2(13), 1-13.

Rutten, M., & Kavalari, A. (2016). Reducing food losses to protect domestic food security in the Middle East and North Africa. African Journal of Agricultural and Resource Economics, 11(2), 118-130.

Rutten, M., & Verma, M. (2014). The impacts of reducing food loss and waste in Ghana: a scenario study using the global economic simulation model MAGNET, LEI Report 2014-035. The Hague: LEI Wageningen.

Rutten, M., Nowicki, P., Bogaart, M., & Aramyan, L. (2013). Reducing food waste by households and in retail in the EU, LEI report 2013-035. the Hague: LEI.

Salemdeeb, R., Vivanco, D. F., Al-Tabbaa, A., & Ermgassen, E. K. (2017). A holistic approach to the environmental evaluation of food waste prevention. Waste management, 59, 442-450.

Secondi, L., Principato, L., & Laureti, T. (2015). Household food waste behaviour in EU-27 countries: A multilevel analysis. Food Policy, 56, 25-40.

Smil, V. (2000). Feeding the World: A Challenge for the Twenty-First Century. Cambridge, MA: The MIT Press.

Smil, V. (2004). Improving efficiency and reducing waste in our food system. Environmental Sciences, 1, 17-26.

Stenmarck, Å., Jensen, C., & Quested, T. (2016). Estimates of European food waste levels. Stockholm: FUSIONS Project Report.

Teuber, R., & Jensen, J. D. (2016). Food losses and food waste: extent, underlying drivers and impact assessment of prevention approaches, IFRO Report No. 254. Frederiksberg: Department of Food and Resource Economics, University of Copenhagen.

USDA. (2018). US Food Waste Challanges: FAQ. Retrieved 04 23, 2018, from United States Department of Agriculture: https://www.usda.gov/oce/foodwaste/faqs.htm

Valin, H., Havlík, P., Forsell, N., Frank, S., Mosnier, A., Peters, D.,... & van den Berg, M. (2013). Description of the GLOBIOM (IIASA) model and comparison with the MIRAGE-BioF (IFPRI) model. *Crops*, *8*, 3-1.

van der Mensbrugghe, D. (2008). The environmental impact and sustainability applied general equilibrium (ENVISAGE) model. The World Bank.

Vanham, D., Bouraoui, F., Leip, A., Grizzetti, B., & Bidoglio, G. (2015). Lost water and nitrogen resources due to EU consumer food waste. Environ. Res. Lett.(084008), 1-15.

Vaque, L. G. (2015). Food loss and waste in the European Union: A new challange for the food law. European Food and Feed Law Review(1/2005), 20-33.

Ventour, L. (2008). Food we waste. London: WRAP and Exodus market research.

Wang, Z., Wei, S. & Zhu, K. (2013). Quantifying International Production Sharing at the Bilateral and Sector Levels. NBER Working Paper, 19677.

Williams, H., Wikström, F., Otterbring, T., Löfgren, M., & Gustafsson, A. (2012). Reasons for household food waste with special attention to packaging. Journal of Cleaner Production, 24, 141-148.

Wilson, N. L., Rickard, B. J., Saputo, R., & Ho, S.-T. (2017). Food waste: The role of date labels, package size, and product category. Food Quality and Preference, 55, 35-44.

Wirsenius, S. (2000). Human Use of Land and Organic Materials. Modelling the Turnover of Biomass in. Gothenburg: unpublished Doctoral Thesis, Chalmers University of Technology.

Woltjer, G. B., Kuiper, M., Kavallari, A., van Meijl, H., Powell, J. P., Rutten, M. M.,... & Tabeau, A. A. (2014). *The MAGNET model: module description* (No. 14-57). LEI Wageningen UR.

WRAP. (2009). Household food and drink waste in the UK, Banbury. Retrieved from http://wrap.org.uk/sites/files/wrap/HouseholdfoodanddrinkwasteintheUK-report.pdf.

Xue, L., Liu, G., Parfitt, J., Liu, X., Herpen, E. V., Stenmarck, Å., et al. (2012). Missing Food, Missing Data? A Critical Review of Global Food Losses and Food Waste Data. Environ. Sci. Technol., 51(12), 6618-6633.

List of abbreviations and definitions

BCFN	Barilla Centre for Food and Nutrition
CAP	Common Agricultural Policy
CAPRI	Common Agricultural Policy Regional Impact
CAPRI-RD	CAPRI – The Rural Development Dimension
CES	Constant elasticity of substitution
CET	Constant elasticity of transformation
CGE	Computable general equilibrium
CH4	Methane
CNS	Constraint non-linear system
CO2	Carbon di oxide
EC	European Commission
DG-ENV	Directorate-General for Environment
ENVISAGE	Environmental impact and sustainability applied general equilibrium
EU	European Union
EV	Equivalent Variation
FAO	Food and Agriculture Organization of United Nations
FGAS	Fluorinated gas
FLW	Food Loss and waste
FSC	Food supply chain
GAMS	General Algebraic Modelling System
GDP	Gross domestic Product
GEMPACK	General Equilibrium Modelling Package
GGIG	Gams Graphical User Interface Generator ()
GHG	Greenhouse gas emissions
GLOBIOM	Global Biosphere Management Model
GTAP	Global Trade Analysis Project
GTAP-AEZ	Agro-Ecological Zones
GTAP-AGG	GTAP-Aggregator
GTAP-AGR	GTAP-Agriculture Model
GTAP-E	GTAP-Energy Model
GTAP-WATER	GTAP-Water Model
GVCs	Global Value Chains
HLPE	High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security
IAM	Integrated Assessment Model

IMAGE	Integrated Model to Assess the Global Environment
IPR	Intellectual property right
JRC	Joint Research Centre
LEITAP	Landbouw Economisch Instituut Trade Analysis Project
MAGNET	Modular Applied General Equilibrium Tool,
METRO	Modelling trade at the OECD (model)
MIRAGE	Modelling International Relationships in Applied General Equilibrium
MRIO	Multi-Regional Input-Output
N2O	Nitrous Oxide
NUTS2	Nomenclature of territorial units for statistics) – Level 2
R&D	Research and development
RHOMOLO	Regional Holistic Model
TiVA	Trade in Value Added
USDA	United States Department of Agriculture
VA	Value added

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Annexes

Annex 1. Implementation of the TiVA indicators

Import shares

In the standard GTAP model, the Armington agents share the lower nest which splits up total import demand to the different origins. The TiVA matrix to invert hence needs to use these shares to convert the total import demand of an activity *a* for a commodity *i* into bi-lateral import demand.

In first step, we calculate bi-lateral import shares based on CIF prices plus import taxes, by first assigning the value (quantity times price)

```
*
*     --- import shares, reconverted into fob
*
     $$iftheni.MRIO "%modulesGTAP_MRIO%"=="on"
       p_impShares(rsNat,rsNat1,iIn(i),%arg1%) $ pmCif.l(rsNat1,i,rsNat,%arg2%)
           = p_results(rsNat,"Q",i,rsNat1,"int",%arg1%,"%version%")
            * (pmCif.l(rsNat1,i,rsNat,%arg2%)*(1+imptx(rsNat1,i,rsNat,%arg2%)));
     $$else.MRIO
       p_impShares(rsNat,rsNat1,iIn(i),%arg1%) $ pmCif.l(rsNat1,i,rsNat,%arg2%)
           = p_results(rsNat,"Q",i,rsNat1,"imp",%arg1%,"%version%")
              * (pmCif.l(rsNat1,i,rsNat,%arg2%)*(1+imptx(rsNat1,i,rsNat,%arg2%)));

     $$endif.MRIO
```

And next converting into shares by calculating the total and dividing by it:

```
*
*   --- scale imports to unity by calcuation of total and division by total
*
     p_impShares(rsNat,"wor",iIn(i),%arg1%)   =
sum(rsNat1,p_impShares(rsNat,rsNat1,i,%arg1%));
     p_impShares(rsNat,rsNat1,iIn(i),%arg1%) $ p_impShares(rsNat,rsNat1,i,%arg1%)
                             =
p_impShares(rsNat,rsNat1,i,%arg1%)/p_impShares(rsNat,"wor",i,%arg1%);
```

Trade margin demand

We next set back to f.o.b. basis:

```
     p_impShares(rsNat,rsNat1,iIn(i),%arg1%) $ p_impShares(rsNat,rsNat1,i,%arg1%)
     = p_impShares(rsNat,rsNat1,i,%arg1%)
        /((pmCif.l(rsNat1,i,rsNat,%arg2%)*(1+imptx(rsNat1,i,rsNat,%arg2%)));
```

That re-definition is necessary to reflect that trade margins in GTAP are defined relative to f.o.b. and request also composite input demand. We hence first calculate the physical total (implicit) trade margin demand for margin products *m* for the production activity *a* in regions *rsNat*:

```
*
*    --- assign output used for trade margins to IO coefficients
*
     p_trdMrg(rsNat,"tot",m,a,%arg1%)
*
*       --- imports from rsNat1 of all products
*
        = sum(((rsNat1,i) $ p_impShares(rsNat,rsNat1,i,%arg1%),
*
*          --- total imports times times shares
*
           p_results(rsNat,"Q",i,a,"imp",%arg1%,"%version%") *
p_impShares(rsNat,rsNat1,i,%arg1%)
*
*          --- global margin demand
*

               * tmarg(rsNat1,i,rsNat,%arg2%) * amgm(m,rsNat1,i,rsNat));
```

And next consider the impact of price changes:

```
     p_trdMrg(rsNat,rsNat2,m,a,%arg1%)
       = p_trdMrg(rsNat,"tot",m,a,%arg1%)
            * sum(tmg,alphaa(rsNat2,m,tmg,%arg2%)
             * ptmg(m,%arg2%)/(pa(rsNat2,m,tmg,%arg2%)/lcu(rsNat2,%arg2%)))**sigmamg(m));
```

Setting up the matrix to invert

The global matrix to be inverted considers:

1. The demand for imported intermediate goods, distributed based on the import shares defined above.
2. The implicit demand linked to the trade margins.
3. The demand for domestic intermediate goods.

as costs (see code below). It is set in relation to total output and subtracted from unity. The residual captures the value added net of import taxes plus any taxes paid on factors or intermediates. That residual thus is relevant for total regional income.

```
option kill=p_IA;
p_IA(n1,n)  $ (nCur(n) $ nCur(n1))
  = 1 $ sameas(n,n1) - sum(((n_r_i1(n1,rsNat1,i),n_r_a(n,rsNat,aIn(a))),
        [
*     --- import demand net of trade margins and import/export taxation => demand in
exporter country rsNat1, fob basis
*                 (only quantities, taxes on ND will become part of income multiplier)
    p_results(rsNat,"Q",i,a,"imp",%arg1%,"%version%") * p_impShares(rsNat,rsNat1,i,%arg1%)

*       --- trade margin demand by activity a for product i in exporter country rsNat1
*
    + p_trdMrg(rsNat,rsNat1,i,a,%arg1%)
*
*   --- demand for domestic origin (again, without taxes on intermediates)
*
    + p_results(rsNat,"Q",i,a,"dom",%arg1%,"%version%") $ sameas(rsNat,rsNat1)
        ])
/sum(n_r_a(n,rsNat,aIn(a)),p_results(rsNat,"Q","out",a,"tot",%arg1%,"%version%"));
```

Technically, only a two-dimensional matrix can be inverted in GAMS. We therefore define a mapping set *n_r_a* which links a combination of a demander region *rsNat* and a demander activity *a* to an index in the matrix to invert. A matching set *n_r_i1* performs the same operation for the combined of importer region *rsNat1* and intermediate commodity demanded *i*.

We use the invert utility which is part of a GAMS release to efficiently invert the global matrix:

```
*
*    --- invert (I-A)
*
     option kill=p_IAInv;
     execute_unload '%scrdir%/p_IA.gdx',nCur,p_IA;
     execute '=invert.exe %scrdir%/p_IA.gdx nCur p_IA %scrdir%/p_IAInv.gdx p_IAInv';

     execute_load '%scrdir%/p_IAInv.gdx',p_IAInv;
```

The income contribution is defined as:

```
*    --- calculate VA share (plus taxes on intermediates and primary factors) of each
commodity, fob basis
*       = all what is not intermediate consumption domestic or imported
*
     p_vaShare(n)   = sum(n1, p_ia(n1,n));;
```

Defining the global multiplier matrix

Based on these shares and global Leontief inverse p_IAIinv returned by the invert utility, we can set up the multiplier matrix. A check ensures that the multiplier matrix adds row-wise to unity.

```
*
*    --- define multiplier matrix
*
     p_int(n,n1) = p_vaShare(n) * p_IAInv(n,n1);
     p_test(n1,%arg1%)    = sum(n, p_int(n,n1));
     p_test("Sum",%arg1%) = sum(n, p_test(n,%arg1%));
     if ((abs(p_test("sum",%arg1%) - card(nCur))/card(nCur) gt 1.E-5,
        abort "Trade in VA multiplier do not add up to unity",p_test);
```

Given the global multiplier matrix multiplied with value added share, we can now define the bilateral multipliers. That relation does however only hold for a diagonal make matrix where each sector outputs exactly one commodity. For the case of a non-diagonal make structure where several sectors output the same commodity as in our study for irrigation and non-irrigated crop,s we define a distribution vector *p_aDist*:

```
*
*    --- share of activities of a on out, relevant for non-diagonal make
*
   p_aDist(rsNat,a,%arg1%) = 1;
   p_aDist(rsNat,a,%arg1%) $ (p_results(rsNat,"Q","out",a,"tot",%arg1%,"%version%") $ (not
diag(a)))
       =  p_results(rsNat,"Q","out",a,"tot",%arg1%,"%version%")
        /sum(a_a(a,a0), p_results(rsNat,"Q","out",a0,"tot",%arg1%,"%version%"));
```

With that additional piece of information, the multiplier matrix can be set up:

```
*
*    --- VA increase for output a in rsNat if commodity j's demand
*        is increased by one unit in rsNat1
     p_results(rsNat1,rsNat,i,aIn(a),"tradeInVaM",%arg1%,"%version%") $ iIn(i)
      =  sum((n1 $ n_r_i1(n1,rsNat1,i), sum(n $ n_r_a(n,rsNat,a),p_int(n,n1)) *
p_aDist(rsNat,a,%arg1%));
```

Applying the global Leontief inverse

We apply the global value added multipliers to the trade vector of region *rsNat*, in order to define the income contribution of exporting product j via activity a, bi-laterally and to all other regions:

```
* --- VA in domestic activity a linked to exports of product j

  p_results(rsNat,"Q",i,aIn(a),"tradeInVa",%arg1%,"%version%") $ iIn(i)
   = p_results(rsNat,rsNat,i,a,"tradeInVaM",%arg1%,"%version%")
       * p_results(rsNat,"Q",i,"exp","dom",%arg1%,"%version%");

* --- VA in ROW activity a linked to export of product j

  p_results(rsNat,"QW",i,aIn(a),"tradeInVa",%arg1%,"%version%") $ iIn(i)
   = sum(rsNat1 $ (not sameas(rsNat,rsNat1)),
p_results(rsNat,rsNat1,i,a,"tradeInVaM",%arg1%,"%version%"))
       * p_results(rsNat,"Q",i,"exp","dom",%arg1%,"%version%");
```

The indicator “tradeInVa” allows to retrieve the domestic and the foreign value added embedded in each country’s exports.

Final demand attribution

Next, we attribute sectoral outputs to final demand.

First, we define the output multipliers showing the total output which is required, both directly and indirectly, to produce one unit of final demand:

```
*
* --- define output multipliers
*
p_results(rsNat1,rsNat,i,aIn(a),"tradeInXPM",%arg1%,"%version%") $ iIn(i)
   =  sum((n1 $ n_r_i1(n1,rsNat1,i),
        sum(n $ n_r_a(n,rsNat,a),p_IAInv(n,n1))
         * p_aDist(rsNat,a,%arg1%));
```

Second, we calculate the domestic and imported final demand in region *rsNat*, based on F.O.B. prices for the imported value:

```
*
* --- calculate domestic and imported final demand, later net of trade margins, fob basis
*
  p_Dem(rsNat,i,"dom",%arg1%)
   = sum(fd $  (not sameas(fd,"trdmg")),
       p_results(rsNat,"Q",i,fd,"dom",%arg1%,"%version%"));

  p_Dem(rsNat,i,"imp",%arg1%)
   = sum(fd $  (not sameas(fd,"trdmg")),,
       p_results(rsNat,"Q",i,fd,"imp",%arg1%,"%version%"));
```

Third, we compute the trade margin demand related to final consumption:

```
*
*  --- asign demand for trade margins from final demand
*
  p_trdMrg(rsNat,"tot",m,"fd",%arg1%)
    = sum(((rsNat1,i),  p_Dem(rsNat,i,"imp",%arg1%)  * p_impShares(rsNat,rsNat1,i,%arg1%)
              * tmarg(rsNat1,i,rsNat,%arg2%) * amgm(m,rsNat1,i,rsNat));

  p_trdMrg(rsNat,rsNat2,m,"fd",%arg1%)
    = p_trdMrg(rsNat,"tot",m,"fd",%arg1%)
         * sum(tmg,alphaa(rsNat2,m,tmg,%arg2%)*(ptmg(m,%arg2%)
         /(pa(rsNat2,m,tmg,%arg2%)/lcu(rsNat2,%arg2%)))**sigmamg(m));
```

Finally, we use output multipliers to attribute output to the final demand:

```
*
* --- attribute outputs to final demand
*
p_results(rsNat,"Q",i,a,"QTiva",%arg1%,"%version%") $ iIn(i)
  =  p_Dem(rsNat,i,"dom",%arg1%) * sum((rsNat1,
p_results(rsNat,rsNat1,i,a,"tradeInXPM",%arg1%,"%version%")))
   +  sum(rsNat1, (p_impShares(rsnat,rsNat1,i,%arg1%)*p_dem(rsNat,i,"imp",%arg1%)
              + p_trdMrg(rsNat,rsNat1,i,"fd",%arg1%))
               * sum(rsNat2,
p_results(rsNat1,rsNat2,i,a,"tradeInXPM",%arg1%,"%version%"))));

p_results(rsNat,"Q",i,a,"QTivaDom",%arg1%,"%version%") $ iIn(i)
   =  p_Dem(rsNat,i,"dom",%arg1%)  *
p_results(rsNat,rsNat,i,a,"tradeInXPM",%arg1%,"%version%")
   +  sum(rsNat1, (p_impShares(rsnat,rsNat1,i,%arg1%)*p_dem(rsNat,i,"imp",%arg1%)
              + p_trdMrg(rsNat,rsNat1,i,"fd",%arg1%))
               *              p_results(rsNat1,rsNat,i,a,"tradeInXPM",%arg1%,"%version%"));
```

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