Can Food Waste Reduction in Europe Help to Increase Food Availability and Reduce Pressure on Natural Resources Globally?

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Abstract

In recent years, reducing food waste and loss has become a policy priority in the European Union, but little is known about impacts of related measures in the EU and beyond. This study informs the debate on food waste reduction through a quantitative analysis. It considers adjustment costs for reducing food waste in food processing industries and impacts on food availability, pressure on land and water and other environmental consequences. The results suggest that the leakage effects of global trade may offset almost all benefits of food waste reduction in the EU. We thus conclude that costly efforts to reduce food waste in the EU cannot be motivated by larger contributions to global food availability and environmental benefits. This highlights the need for global coordination of such policies and/or more targeted actions in the EU which focus on specific production chains, where losses can be reduced and environmental gains obtained at a relatively low cost.

Key Words

policy analysis; food loss and waste; food availability; environment; simulation

1 Introduction

Questions surrounding 'food waste'[1] have gained more attention recently where the connotation "waste" often carries an ethical imperative to increase food availability for the hungry through less waste from the rich. Reducing food waste is also motivated by increasing biomass availability for material and energy use, thus easing "green growth". Less food waste shall also reduce pressure on resources such as land and water and thus, decrease negative environmental externalities linked to agricultural food production. These potential benefits have stimulated government action plans. The EU, for example, has placed reducing food waste among its top priorities. The Circular Economy Package with 'a zero waste programme for Europe' was launched in 2014 (EUROPEAN COMMISSION, 2014a) and the 2018 Revised EU Waste Legislation (THE EUROPEAN PARLIAMENT, 2018) has called on the EU countries to actively monitor and reduce food waste at each stage of the food supply chain (FSC). THE EUROPEAN PARLIAMENT (2018) also has set a non-binding 30% target for food waste reduction by 2025, rising to 50% by 2030. In the global context, these objectives are in line with the Sustainable Development Goal (SDG) 12, formalized by the United Nations (UNITED NATIONS, 2015) to foster "responsible consumption and production". Under these SDGs, the target 12.3 explicitly refers to halving per capita global food waste at different stages of the FSC. Such targets and related actions however, contrast with the many uncertainties about the current degree of food waste (XUE et al., 2017)) and even more so about the impacts of its reduction (HOJGARD et al., 2013), a field with little scientific findings so far. Thus, the prime motivation of this paper is to investigate the impact of food waste reduction policies. The impacts will be evaluated on food availability, consumer welfare, use of resources such as land and water and Greenhouse Gas (GHG) emissions both at the EU level and globally.

[1] In this paper we do not distinguish between waste and loss and instead use the term 'food waste' throughout the text, that include losses as well.

As summarised in Appendix A, there are different definitions of food waste and data matching these definitions are at an infancy stage. Each implies differences on how to quantify total waste, which under the same relative reduction target also means different costs and other impacts. Furthermore, literature often translates food waste reduction into higher productivity, i.e., more output with the same resources or less resources for the same output (RUTTEN and KAVALLARI, 2016; RUTTEN et al., 2015; among others). This neglects potential (adjustment) costs related to lower food waste and related impacts, a point of focus in our analysis.

Some studies (RUTTEN, 2013, for example) treat food waste reduction efforts as "manna from heaven", i.e. they assume that more food can be produced (or used) at unchanged amounts of biomass and other inputs. This perspective violates standard economic assumptions as cost minimizing firms should technically produce efficiently, i.e. not use more inputs than necessary and utility maximizing consumers should not spend money (and efforts) on goods they do not plan to consume, at least in the aggregate. The issue is not a purely theoretical one: modeling food waste reduction as less food input per unit of output (a productivity gain) should simultaneously consider that this change in input-output relations entails some implementation costs. Otherwise, quantitative analysis runs the risk of incorrectly informing the public debate about food waste. In line with this argument, TEUBER and JENSEN (2016) stress that reducing food waste is not costless, but requires productive resources. They therefore introduce the concept of "optimal food waste". From an economic perspective "optimal food waste" refers to the situation where the marginal cost of preventing food waste is equal to its marginal benefit. Accordingly, policies aiming at the reduction of "optimal food waste" need to balance the expected changes both in marginal benefits and costs.[2] This study models food waste reduction by improvements in partial factor productivities associated with utilisation of agricultural goods in the food processing industry while increasing the usage of all other production factors in the sector, to ensure that mainstream economic assumptions about preferences and rationality at the benchmark are respected. Equally, it refrains from making any normative consideration about individual or social preferences, meaning that we take choices as they are, not as they "should be", according to some ethical principle. This, however, contrasts with the implicit moral judgment associated with the word "waste", recalling not only inefficiency but also injustice and deprecated behaviour. In addition,, rationality, as assumed in the model used by us, implies that observed food waste is the outcome of voluntary choice considered optimal by the individual making that choice. In other words, observed food 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.

Here, distinguishing between fixed and variable implementation costs is important. All costs considered in this study are variable: it is assumed that the food processing sector employs more non-agricultural inputs when the food input is reduced. There may be cases, however, where efficiency improvements (in this case, in the utilization of agricultural inputs), are made possible by specific investments, for instance, into 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. An especially interesting case in this context is when investments in food waste reduction have the nature of a public good, i.e. if consumption by one agent does not exclude others such that public sector provision is favourable. For example, in the context of food waste reduction, we could envisage an investment in a public information campaign as a public good, capable of permanently reducing food waste by final consumers.

More generally, individual choices about food waste, even if rational, are not socially optimal when social values deviate from private ones. In this case, government intervention might help to correct externalities and market failures related to food waste, such as by informational campaigns. For instance, suppose that consumers only want perfectly rounded and red apples, so farmers dispose other ones. You may consider discarding "imperfect" yet fully eatable apples a "waste", but from a scientifically neutral perspective, we take such consumer preferences as given and rather pose the questions: are there socially valuable uses of "imperfect apples"? If such options exist, why are they not exploited by the apple supply chain? What kind of economic incentives can be offered to realign individual behaviour to social objectives?

We are not the first to take the adjustment cost into account. BRITZ et al. (2014), in their analysis of

[2] Note that when the amount of food waste is optimal from individual perspectives, it does not necessary means that it is optimal from social perspective [see TEUBER and JENSEN (2016) for more details].

food waste reduction at household level in the Netherlands, reflect food reduction costs by considering related efforts by households, like spending more time preparing food. Similarly, PHILIPPIDIS et al. (2019) analyse the impact of food waste reduction in the EU at household level by considering adjustment costs. Our study complements BRITZ et al. (2014) and PHILIPPIDIS et al. (2019) by focusing on the impact of food waste reduction in the food processing industry, explicitly accounting for the costs of reduced food waste. Specifically, considering an estimated 19% overall share in food waste by the processing sector in the FSC (STENMARCK et al., 2016; TONINI et al., 2017) and given the targeted 30% reduction in total food waste by the EU, we consider a 5% reduction in the volume of food waste as a target. As related costs in different branches of the food processing are vastly unknown, we perform a sensitivity analysis considering different levels of food waste reduction costs.

All the considerations above bring us to model food waste reduction policies in the food processing industry as a shift in its input demand structure: less demand for agricultural products, more demand for other goods and services. Our analysis therefore requires a multi-sectoral perspective, where market interdependences are fully taken into account and the welfare impacts can be identified. This objective is reached through the use of a rich data set, exploited by means of a Computable General Equilibrium (CGE) model, which allows for the consideration of all adjustment processes taking place in the economic system and highlights distributional consequences of food waste reduction policies.

Furthermore, in order to quantify some major impacts on the environment and natural resources, we employ a CGE model with special features such as substitution of intermediate inputs in agricultural and food processing sectors, modelling of water as an explicit factor of production, disaggregation of land in terms of agro-ecological zones and consideration of CO_2 and non- CO_2 emissions. Furthermore, we depict production and factor use for EU countries at the level of 280 sub-national regions, especially in order to gain insight into the impact on agriculture and related resource use at regional level.

2 Related Literature

Following a study by FAO (2013) on food waste, a vast variety of literature emerged which highlights various negative impacts of food waste. The original study by FAO (2013) estimated that food waste accounts globally for 3.3 gigatonnes of CO_2 equivalents and implies inefficient usage of 250 km^3 of water each year, according to KUMMU et al. (2012) equivalent to 23% of global water use, as well as requiring 30% of the global cropland. As a follow-up, FAO (2014b) estimates the global annual cost related to food waste at 2.6 trillion USD, equivalent to as much as 3.3% of global GDP. Of that total, one trillion USD is attributed to the production costs of the wasted food. “Social costs”, referring to hunger and conflict risks, are gauged at 882 billion USD. The remaining 700 billion USD is associated with environmental impacts, mainly GHG emissions (305 billion USD) and water use (165 billion USD). The importance of food waste is also highlighted by MONIER et al. (2010), who estimates that food waste accounts for 3% of total GHG emissions in the EU.

Food waste occurs at different stages of the FSC which consists of primary agriculture, food processing industries that transform agricultural outputs and other inputs to food and the wholesale and retail sector that distributes the output of the food processing industry to the final point of use (i.e., households, caterers, canteens, restaurants etc.). The majority of studies come to the conclusion that food waste mostly occurs during food processing and at the household level. For example, MONIER et al. (2010) report that 42% of food waste in Europe occurs at the household level and 39% in food processing, while the distribution and food service sectors account for 5% to 14% of food waste, respectively. That study, however, does not cover food waste at the production stage of primary agricultural products. Taking the latter into account, STENMARCK et al. (2016) find that 53% of food waste is taking place at the household level, 19% during intermediate processing, 10% during primary production, 12% in the food-service sector and 5% in the distribution sector. BERETTA et al. (2013) also find similar results for Switzerland, stating that 45% of the food waste is occurring at the household level, while food processing follows, with 31%. On the other hand, some studies report that food waste loss is less pronounced in the processing sector. TONINI et al. (2017) find that 19% of food waste in Denmark is at the processing phase, while van der WERF and GILLILAND (2017) report that the estimates of food waste in the food processing sector is generally lower than retail by comparing 55 studies in the literature. It should be noted that shares of food waste at different stages of the FSCin developing countries might look rather different.

In recent years with increased political awareness of food waste, several global initiatives to tackle food waste emerged. Food waste reduction is one of the SDGs and many countries and regional organizations set targets accordingly to reduce food waste. International organizations such as FAO and UN Environmental Agency are cooperating with regional organizations to develop policy frameworks and to disseminate best practices. These efforts lead the way for important achievements, such as standards to measure food waste (THE FOOD LOSS & WASTE PROTOCOL, 2019) to address the ambiguity of the definition of food waste. However, effects of these efforts are yet to be observed in the amount of food waste reductions (HAMILTON and RICHARDS, 2019).

Different approaches and methodologies are used to analyse food waste in applied economic studies: single country CGE models (CAMPOY-MUNOZ et al., 2017; BRITZ et al., 2014), global multi-regional CGE models (RUTTEN et al., 2013; RUTTEN and VERMA, 2014; RUTTEN and KAVALLARI, 2016), Partial Equilibrium (PE) models (HOJGARD et al., 2013) as well as econometric methods (ELLISON and LUSK, 2018; BAHADUR et al., 2016; SOMKUN, 2017). Most studies find that reduced food waste brings about: (1) significant economic benefits and reduced environmental impacts from agricultural production, (2) improved food safety (RUTTEN and VERMA, 2014; RUTTEN and KAVALLARI, 2016), (3) a decline in agricultural production and (4) limited impacts on real GDP (RUTTEN et al. 2013; CAMPOY-MUNOZ et al., 2017). Marginal environmental and economic benefits are found by HOJGARD et al. (2013), the latter mainly due to lower food prices. However, impacts on real GDP especially depend on the assumptions of if and how costly food waste is.

In terms of distributional consequences, most studies show that global net effects of food waste reduction efforts in one region versus impacts in the rest-of-the-world (ROW) depend on many factors, such as the food trade balance and supply and demand factors. CAMPOY-MUNOZ et al. (2017) and HOJGARD et al. (2013) report different impacts across countries or regions of the same country, as well as between producers and consumers. The EUROPEAN COMMISSION (2014b) reports that food waste reduction would benefit food processors, while agricultural producers and retailers are likely to be worse off.

A major shortcoming of almost all studies cited above is that they do not take into account the costs involved in reducing food waste. Indeed, only a few of them consider what TEUBER and JENSEN (2016) have termed "optimal food waste", where marginal cost of food waste reduction equals its marginal benefit. Currently observed levels of food waste may thus be privately optimal, reflecting consumer preferences and cost minimization; however, as in other fields, they could also partially be a consequence of irrational behaviour, asymmetric information, or organizational problems (FAO, 2014c). Not surprisingly, the few studies that take into account implementation costs of food waste (and rational economic decisions), qualitatively (KOESTER, 2014) or quantitatively (ELLISON and LUSK, 2018), suggest lower benefits of food waste reduction (KOESTER, 2014; ELLISON and LUSK, 2018).

If observed food waste is (to some degree) privately optimal, policies aimed at reducing food waste will generate some costs and thus require resources (CHABOUD and DAVIRON, 2017). Contrasted with the (implicit) "free lunch" hypothesis, accounting for costs of food waste lowers both the expected increase in food availability and environmental benefits. For example, cold storage facilities consume energy, donating excess food to food banks requires transportation of food and better packaging might require the use of more materials that are harmful to the environment. Furthermore, food waste efforts could face the Jevons paradox (see POLIMENI et al., 2008) where savings in energy and water as well reduced emissions of reduced food waste due to an efficiency increase will be partly offset due to higher demand at lower costs and thus prices. In the case of food waste, requiring producers (in the EU) to use less agricultural input to produce food makes agricultural commodities cheaper and thus induces demanders (in the EU and globally) to use more agricultural commodities. SALEMDEEB et al. (2017) report that 60% of the GHGs reductions due to food waste prevention may be offset due to rebound effects, i.e. GHGs emissions created by prevention measures themselves. RUTTEN (2013) confirms this based on a simple PE analysis where net GHG savings from food waste reduction are ambiguous.

Recent studies by BRITZ et al. (2014) and PHILIPPIDIS et al. (2019) focus on food waste at the household level, considering the efforts necessary for its reduction, such as spending more time for food preparation. Food preparation is framed as an activity that uses both time – competing with leisure and work outside the household – and intermediate inputs to convert the food bought by the household to the food actually consumed. Our paper complements the literature by analysing food waste reduction at the food processing stage, while also depicting the trade interactions among regions and considering impacts on land use, water and GHG emissions. To the best of our knowledge, this is the first study with these specific characteristics.

3 Methods and Data

The provision of food in industrialized economies is based on complex value chains integrating firms from agricultural, food processing and distribution sectors. Efforts to reduce food waste at any stage will have market and thus, price mediated consequences along these chains. Technical measures to reduce food waste, such as improved cold chains, impact non-food intermediate and factor demand even more so and thus have consequences beyond food-related value chains, requiring a multi-sector perspective. Since markets affected by food waste reduction are inter-connected via national and international trade, modelling an increase in food availability requires a broad and systemic approach. We therefore opt for a global CGE analysis and depart from the well documented and tested Global Trade Analysis Project (GTAP) Standard model[3], to which we add features especially important for the analysis at hand.

We use the flexible and modular CGE modelling platform CGEBox (BRITZ and VAN DER MENSBRUGGHE, 2018). It is encoded in the General Algebraic Modelling Language (GAMS) and uses the available GTAP database version 9 for which satellite data on emissions and land use are also available. CGEBox departs from Version 7 of standard GTAP model (VAN DER MENSBRUGGHE, 2018) as a core to which the modeller can flexibly add modules, change or add different nestings for the production structure and factor markets or change the structure of modelling international trade. A complete documentation of this platform can be found in BRITZ (2017).[4]

The appropriate (and efficient) combination of the available modules depends on the issue at hand. Due to our focus on food processing and agriculture, we add to the standard GTAP model the features of GTAP-AGR (KEENEY and HERTEL, 2005), i.e. segmented factor markets and specific nestings in agricultural production. Furthermore, to quantify impact on land and water use, as well as on GHGs, we add the modules GTAP-water (HAQIQI et al., 2016), to distinguish between irrigated and non-irrigated agriculture and GTAP-AEZ, where physical land use is disaggregated in terms of Agro-Ecological Zones (AEZs), based on HERTEL et al. (2009). The GTAP-AEZ module integrated with the Non-CO_2 emission database (GIBBS et al., 2014) together with the GTAP 9 CO_2 emission database allows analysing the changes in GHGs. Lastly, we are interested in looking into the land use and GHGs at sub-national regions across the EU for which we employ a module in CGEBox (BRITZ, 2017) which offers a breakdown of production and factor use for sub-regions.[5] The introduction of these different modules into the GTAP model implies that the production structure differs across industries.

The next section provides an overview on the standard GTAP model and discusses in more detail the extensions we introduced. Full detail of the modelling framework and its GAMS implementation is provided in the Online Appendix.[6]

3.1 Structure of the Standard GTAP model

The standard GTAP model (HERTEL, 1997) is a comparative static, global CGE model based on the Walrasian general equilibrium structure. The equations, its parameters and structure of the data of the latest version 7 of the GTAP model are fully described in VAN DER MENSBRUGGHE (2018). The standard GTAP model assumes cost-minimizing behavior under constant returns to scale (CRS) production technologies along with utility maximizing consumers in competitive markets. There is a single virtual representative household in each region that owns the production factors and receives factor

[3] As documented in Hertel, T.W. and M.E. Tsigas "Structure of GTAP", Chapter 2 in HERTEL (1997)

[4] http://www.ilr.uni-bonn.de/em/rsrch/cgebox/cgebox_e.htm covers full documentation, including information how to download the code and additional material (i.e., training videos).

[5] The module uses for the EU data at the level of administrative NUTS2 regions, equivalent to Regierungsbezirke for Germany.

[6] The online Appendix can be found in http://www.ilr.uni-bonn.de/em/rsrch/cgebox/cgebox_GUI.pdf.

returns, net of taxes. That so-called, “regional household”, also collects income from taxation such as tariff revenues and rents accruing from export or import licenses that are depicted as exogenous ad-valorem price wedges. The regional income is then allocated to different agents (private household, government and saving) based on a modified Cobb-Douglas (CD) utility function.[7] The private household’s demands for Armington commodities are derived from a non-homothetic Constant Difference Elasticity (CDE) implicit expenditure function, which allows for relatively flexible price responses, while government and saving demands for Armington commodities are driven by a constant elasticity of substitution function (CES). The Armington demand for each agent and commodity is defined as a CES composite of domestic and import demand. The import demand composition from bi-lateral trade flows is depicted by a second CES nest.[8]

On the supply side, production is defined as the Leontief aggregate of value added and intermediate inputs bundles; the value added composition is based on a CES aggregate of primary factors (unskilled labour, skilled labour, capital, natural resources, land) while the composition of intermediate demand is based on fixed physical input coefficients (Figure B1). As for the final demand agents, each sector features its own Armington nest to determine the composition of intermediate input demand for each commodity from domestic production and imports. However, the import composition is identical across sectors and final demand. The model assumes full mobility inside a region for capital, skilled and unskilled labor, sluggish mobility for land and sector-specific and thus immobile natural resources such as fish stocks, rare earths, or fossil oil reserves. Supply of primary production factors is modelled through fixed stocks and in the case of sluggish mobility across industries, governed by a CET[9] allocation mechanism.

The standard GTAP model is accompanied with a global Social Accounting Matrix (SAM) database for different base years. We use the latest version of this database, GTAP9, that comprises data on consumption, production, primary factor use, bilateral trade in goods and services, intermediate inputs among sectors, as well as taxes and subsidies imposed by governments and CO_2 emissions for 140 regions and 57 commodities for the year 2011, as well as data on land and irrigation water use.

3.2 GTAP-AGR Production Structure

In order to better capture some particular features of agricultural activities, KEENEY and HERTEL (2005) introduce some modifications to the standard GTAP structure. Among them, we apply the changes in the production structure. We follow GTAP-AGR in differentiating the supply of mobile factors (labour and capital) between agricultural and non-agricultural activities using a two-tier CET mechanism (Figure B2). Furthermore, contrary to the standard GTAP model, where intermediate factor demand is driven by fixed input-output coefficients, we introduce (as in GTAP-AGR) a sub-nest under the intermediate input composite for the livestock and food processing sectors to allow for the substitution of “feedstuffs” (Figure B3).

3.3 Irrigation Water as an Explicit Production Factor

We follow the GTAP-WATER framework (HAQIQI et al., 2016) to incorporate irrigation water as an explicit input and to account for substitution possibilities between water and other primary factors. The water data in HAQIQI et al. (2016) break down returns to land into “land rents” and “irrigation water rights rents” and distinguishes between irrigated and rainfed variants for the eight cropping activities from the GTAP database. The model allocates irrigation water across irrigated cropping activities using a CET mechanism. The production structure of irrigated crops is shown as in Figure B4; for rainfed crops, Figure B3 applies. HAQIQI et al. (2016) provide four different versions of the GTAP-WATER database that differ in the spatial and regional detail of irrigated and rainfed crop productions. We use the version GTAP-WATER-V9-A which fits bests to our modelling structure and the regional aggregation. It is organised as a diagonal input-output make matrix, i.e. there are not only irrigated and non-irrigated production activities but also irrigated and non-irrigated products that are differentiated in demand, trade, etc. We therefore re-aggregate to derive a non-diagonal make matrix where irrigated and rainfed activities of the same crop produce an homogeneous output in each region.

[7] Modified CD utility function updates the private consumption share in the regional household income distribution (see CGEBox documentation: http://www.ilr.uni-bonn.de/em/rsrch/cgebox/cgebox_GUI.pdf).

[8] See page 2, Figure 2 in VAN DER MENSBRUGGHE (2018)

[9] Constant Elasticity of Transformation, the supply side dual of the CES function.

3.4 Agro-ecological Zones

Following HERTEL et al. (2009), we spatially break down land into different AEZs (FAO/IIASA, 2000), characterized by climate and soil type. Sectoral demands for land are disaggregated to the different AEZs, using additional CES composites as shown in Figure B5. Likewise, as shown in Figure B6, each AEZ in a region is characterized by a given stock of land in economic use, which is allocated to different land use activities (forestry, pasture and cropping activities) through a CET. For calibration of the model parameters, we employ the GTAP-AEZ Land Use Data Base (LEVANO et al., 2015) which contains data in hectares by type of land cover (cropland, forests and pasture) and up to 18 AEZs for each region in the GTAP9 database.

Employing GTAP-AGR, GTAP-WATER and GTAP-AEZ implies that the production structure of different industries is not identical. Figure B3 displays the production structure of processed food sectors. The production structure of forestry, rainfed cropping and livestock activities is illustrated in Figure A5. The production structure of other GTAP sectors follows the standard GTAP model specification (Figure B1).

3.5 CO_2 and Non-CO_2 Emissions

CO_2 emissions in the GTAP9 database are based on the energy volume data for each industry and region. The GTAP Non-CO_2 Emissions Database (IRFANOGLU and MENSBRUGGHE, 2016) complements the GTAP9 database by providing information on three other major GHGs: Methane (CH_4), Nitrous Oxide (N_2O) and Fluorinated gases (FGAS). The non-CO_2 emissions are associated with four drivers: output, primary factors (land and capital), intermediate inputs and household consumption. Land carbon stock data (i.e. soil and biomass carbon stock) for different coverage of land (i.e. pasture, cropland and forest) for each AEZ in each region is available from Gibbs (2014). We use this information in the model to capture changes in the total carbon stock due to land cover change in different AEZs and regions.

3.6 Sub-national Detail for EU Countries

The European NUTS system classifies regions into different administrative levels. We use regional SAMs developed by FERRARI et al. (2010) at the NUTS2 level (281 regions for the EU-28 where 21 countries are disaggregated to sub regions and each of the other countries are considered as one single unit in NUTS2 classification) complemented by data from the CAPRI data base (BRITZ and WITZKE, 2012) to disaggregate some macroeconomic variables in the model, using the methodology by BRITZ (2017). Based on the resulting database with sub-national detail, we consider irrigation water and land as regionally immobile, the latter at the level of AEZs, depict other factor supply as sluggish across sub-national units based on CET and specify a production function for each of the industries located in a NUTS2 region.

3.7 Sectoral and Regional Aggregation

In determining the industries and regions considered in our model, we tried to keep all the available information for agri-food sectors. “Forestry” and “Trade” which comprises the retail sector are equally kept as separate industries. The remaining sectors are mostly highly aggregated while retaining some details for providers to agriculture (see Table B1). With regard to regional aggregation, we keep 21 EU Member States as single regions (Finland, Sweden, Denmark, United Kingdom, Ireland, Germany, Netherlands, Belgium, France, Austria, Spain, Portugal, Italy, Greece, Poland, Bulgaria, Romania, Slovakia, Slovenia, Czech Republic, Hungary) with a break-down to NUTS2. Other EU countries in the dataset as single countries are: Estonia, Latvia, Lithuania, Croatia, while three smaller countries (Cyprus, Malta, Luxembourg) form an aggregate. We aggregate the non-EU regions into: North America, Latin America, the Middle East and North Africa, Sub-Saharan Africa, East Asia, Southeast Asia, South Asia, Oceania and ROW. Combined, that leads to a model with 16 crop sectors (8 irrigated and 8 rainfed crops), 37 non-crop activities, 281 NUTS2 regions (covering the EU28) and 9 remaining global regions.

4 Scenario Design

We focus here on food waste in the food processing industry and the related distribution network, leaving out food waste at farm and household level, partly to complement existing studies such as BRITZ et al. (2014) and PHILIPPIDIS et al. (2019) which focus on the household level and partly reflecting how policy measures are likely to address food production and distribution. The underlying database for the CGE analysis is the SAM where the value of food waste is part of intermediate input in the food processing sector. Current estimates indicate that the food processing sector contributes to 39% of the total food waste on the supply side and 19% of the total food waste when both the supply and demand sides are considered. As mentioned above, considering the 19% overall contribution of the processing sector and given the target of 30% reduction in total food waste by the EU, we consider a 5% reduction as a realistic target. We cannot perform a detailed policy impact assessment as this would require legislative proposals which spell out policy measures such as changes in taxes or subsidies, command-and-control measures, etc. Instead, we analyse consequences of a 5% reduction of physical input use of primary agriculture and food products per unit of output in the EU food processing industry, under different assumptions on related costs.

The shocks are technically implemented as follows: Consider the following demand function for the intermediate inputs in line with the extension of the core model to GTAP-AGR (Figure B3) where the intermediate demand for primary agricultural output (the feed-stock component), XA, with the price PA is derived from a CES production function for the intermediate demand composite :[10]

$$XA_{r,i,a} = \alpha^{io}_{r,i,a}\, ND_{r,a}\, \left(\frac{PND_{r,a}}{PA^{a}_{r,i,a}}\right)^{\sigma^{nd}_{r,a}} \left(\lambda^{io}_{r,i,a}\right)^{\sigma^{nd}_{r,a}-1} \quad (1)$$

Here the subscript r specifies the region, i the intermediate input and a the production activity using the intermediate input, respectively. The elasticity of substitution is given by σ^{nd} and zero in the standard GTAP model, but not in our model in case of the food industry. The coefficient λ^{io} denotes the efficiency level, equal to unity in the baseline. The coefficient α^{io} denotes the cost share parameter of the intermediate input in total intermediate demand at the benchmark and ND is aggregate intermediate input bundle. Its price PND is defined as:

$$PND_{r,a} = \left[\sum_{i} \alpha^{io}_{r,i,a} \left(\frac{PA^{a}_{r,i,a}}{PND_{r,a}}\right)^{1-\sigma^{nd}_{r,a}}\right]^{\frac{1}{1-\sigma^{nd}_{r,a}}} \quad (2)$$

We model reduced food waste by increasing the technology shifter λ^{io} related to agricultural inputs in food processing sectors by 5%. That implies changes in input-output relations. Quantities in the CGE are expressed in constant unit dollars and prices are set to unity in the benchmark. Without changing simulated relative changes in quantities and prices, one could switch to physical units instead and redefine the prices accordingly. This underlines that the α^{io} which express cost shares in the benchmark denote also physical input-output relations, for instance, how much wheat or beef the food industry requires to produce one unit of output. Changing λ^{io} by 5% in (1) would hence allow the food industry to save 5% of physical inputs while still produce the same output quantity, i.e. food waste would be reduced. The first order effect of the shock is decreased intermediate demand for agricultural output such that agricultural product prices fall. As the production technology is not Leontief, agricultural input use per unit of output in the food processing sectors will increase again, leading to a "rebound effect". Here, not only the substitution between different inputs matters but as well between the value-added and the intermediate composite. The "rebound" effect partly offsets the assumed change in technology.

Furthermore, as stated above, we don't assume that the 5% input savings comes for free. We estimate the related costs as follows. First, we calculate the costs saved at prices of the benchmark. Next, we increase all other input demands by the same relative change such that a scenario specific share (or multiplier) of the saved costs would be added at benchmark prices. We consider two scenarios which should cover the relevant range of assumed costs:

1. *Cost-neutral scenario*: here, the EU food processing sector can achieve the target quite easily, i.e. we assume that one Euro saved by decreased food waste is offset by another Euro needed to achieve that reduction. That reflects "optimal private food waste" at the benchmark in combination with a rather flexible technology.
2. *Non-cost neutral scenario*: the second scenario is somewhat more pessimistic but possibly more realistic: each Euro saved from agricultural inputs leads to two Euros of additional costs for other inputs.

We also perform a third scenario without adjustment costs for comparison. Furthermore, as we do not aim at analysing in detail specific potential measures – that would require a much more detailed approach, hardly feasible with a global perspective as the one we adopt here – we equally implement the scenarios in all food processing sectors, without differentiation within the EU. The resulting changes in intermediate and factor demand lead to adjustments in the global economy and environmental impacts, which we track with our simulation.

[10] Introduced equations are identical to Equations 6 and 7 in VAN DER MENSBURGHE (2018).

5 Results

We focus on the following three major impacts of reduced food waste which reflect the main issues in the societal debate: increased food availability, reduced pressure on land and water and other environmental benefits. We measure food availability through changes in two variables: (1) domestic production and (2) household consumption. The pressure on land and water resources will be analysed by looking into the pattern of land coverage change and reduced use of water resources. Among other environmental impacts, we consider the reduction in direct and indirect CO_2 equivalent emissions.

Expected impacts from reducing food waste in the European food industry are as follows. As intermediate demand for primary agricultural products drops, supply and prices for agricultural products would decrease and, consequently, returns to agricultural primary factors would reduce, leading to income losses for farmers. Reduced demand for land and irrigation water, as well as less intensive agricultural production practices, might improve environmental quality. Higher demand by the food industry for other inputs could lead to negative environmental impacts such that net effects, e.g. on GHG emissions, are uncertain.

One aim of reducing food waste is to increase food security. Food security is both a matter of regional food availability and of being able to afford food, which depends on income and prices. The impacts are in principle ambiguous. Dropping agricultural prices reduces the income and thus farmers' purchasing power but lead to cost savings in the ROW'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, such that 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 ROW food industry. Equally, lower prices for agricultural products also imply a lower farming income which implies loss of purchasing power.

5.1 Impact on Food Availability

Table 1 presents the simulated changes of agricultural prices in both the EU and globally for both scenarios. As expected, the price of agricultural outputs decreases. In the cost neutral scenario, prices in the EU for primary agriculture products drop, by 0.9% for crop and by 1.1% for animal outputs, on average. As other input prices do not increase much due to higher input demand by the food industry, the production costs and the price of processed food products decreases by 1.2 % on average in the EU. The global reductions are smaller (around -0.2%, -0.3% and -0.4%) reflecting the share of the EU's food processing industry globally and its trade integration.

Variations among prices inside the aggregate groups (crops, animals, processed food) are relatively small (see, Table B2 in the Annex B for detail). Furthermore, there are also some differences in price changes for primary agriculture products across the EU Member States and across global regions (not shown in tables). Across the EU, agricultural price drops can be as large as 2%. There is no single expla-

Table 1. Changes in agri-food markets [% change]

Scenarios	Cost neutral		Non-cost neutral	
	EU	Global	EU	Global
Price of crops	-0.9	-0.2	-1.1	-0.2
Price of animals	-1.1	-0.3	-1.3	-0.3
Price of processed food products	-1.2	-0.4	-0.2	-0.1
Value added in processed food sectors	1.1	0.2	0.2	0.0
Value added in crop production	-0.8	-0.2	-0.8	-0.2
Value added in animal production	-1.5	-0.3	-2.6	-0.4
Land demand	-0.03	-0.07	-0.02	-0.0
Water demand	-0.17	-0.01	-0.19	-0.01
GHGs	-0.3	-0.01	-0.4	-0.02
Farmers income	-0.5	-0.1	-0.6	-0.0
Food consumption	0.16	0.04	0.02	0.00
Welfare (USD per capita)	-0.3	-0.2	-2.0	-1.0

Source: model results

nation for the differences in regional price changes which depend inter alia on the demand composition of the food industry and its sourcing from both domestic and import channels. Primary animal products such as live animals and milk have a tendency to show larger price drops. That reflects higher trade costs compared to crops such as cereals and that that EU meat exports face generally higher tariffs and non-tariff measures, compared to crops and products derived thereof.

As a consequence of lower agricultural prices, food production in the EU increases by 1.1%, compared to 0.2% in the ROW. The net effects of decreased per unit demand by the food processing industry and rebound effects, such as higher overall output by the food processing industry, results in the demand for primary agricultural products (i.e. crops and animals) to shrink by 0.8% and 1.5%, respectively. This finding is in line with other literature analysing food waste in quantitative economic frameworks (HOJGARD et al., 2013; HAMILTON and RICHARDS, 2019), or qualitatively (RUTTEN, 2013; KOESTER, 2014). As a result, we observe a moderate decrease in the pressure on land and water. Impacts on GHG emissions are also not significant as output and input changes across the economy as a whole are small. Furthermore, less CO_2 emissions from lower agricultural output and less land use changes are partly offset by the increase in the use of other intermediate inputs which induce some CO_2 emissions, either directly or indirectly.

Impacts on income of the aggregate agricultural household, which mostly depend on factor income earned in the agricultural sector, are more pronounced with -0.5% in the EU average. A main reason is that return to lands, consistently in all EU Member countries, drop more than agricultural output prices. Sizeable positive changes across regions (not shown in the table) are not found; the maximum is an increase by 0.1% in the ROW; all EU Member countries with the exemption of Finland (+0.0%) show a drop in agricultural income. The impact on food consumption is also expected to be minor (see Table 1).

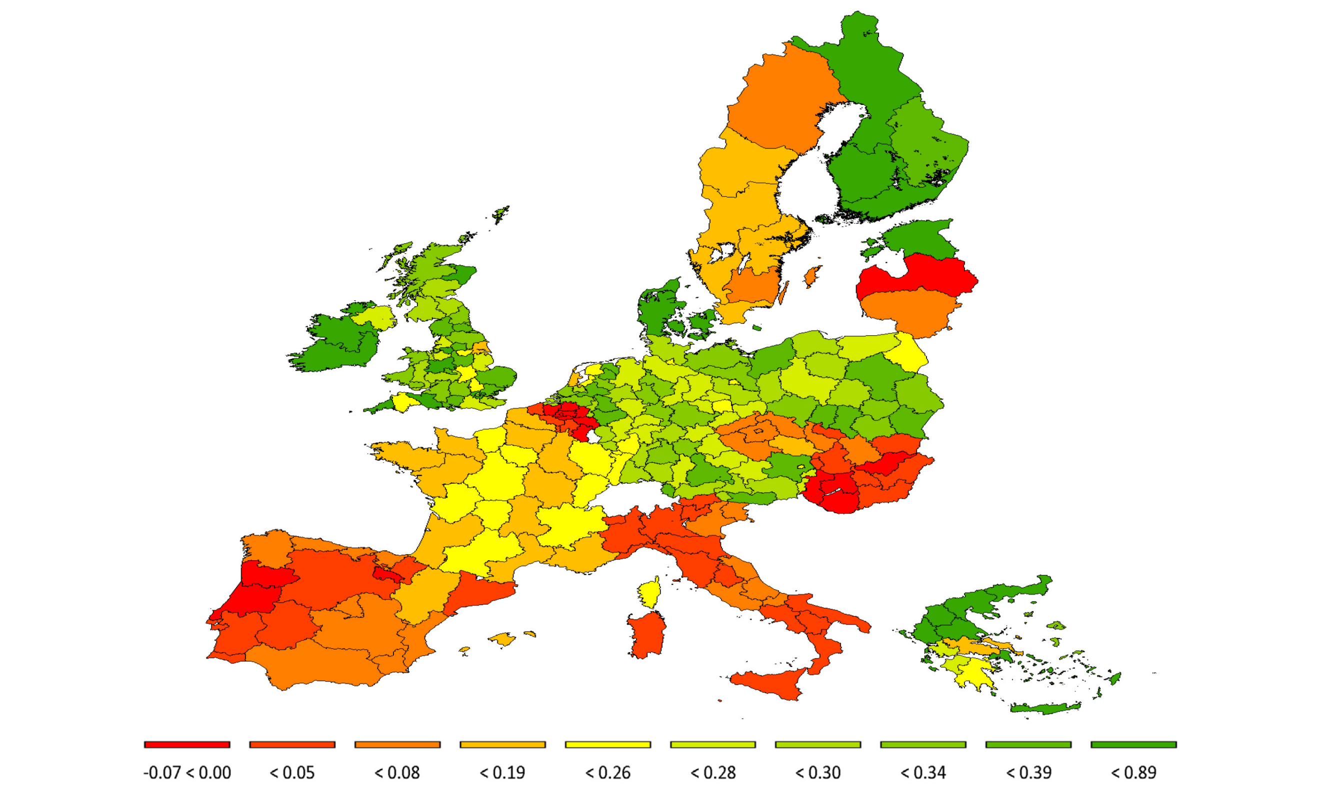
Once moving from the neutral-cost scenario to the second scenario where one dollar of saving from agricultural inputs requires two dollars more of the other intermediate inputs, price drops in processed food products are lower (-0.2%) and there are smaller increases in food products (0.2%), which in turn explain the larger decrease in production of primary agricultural outputs (mainly for animal products), resulting in quite small and mixed impacts on the use of primary inputs. Considering the reduction in primary agricultural products there is no significant differences on the impact on value added for crops across the two scenarios but the reduction in value added for animal products is significantly larger. A possible explanation is that quantities of crop products no longer used domestically due to reduced food waste can be more easily exported than in case of animal ones as also reflected in the price changes discussed above.

We also check outcomes of cost saving scenario where the EU food industry can reduce its use of agricultural and food products by 5% for free, i.e. without producing less or requiring more of other inputs. This improves its production efficiency and competitiveness. Consequently, the demand for food products increases globally, which vastly offsets the reduced input demand for primary agricultural outputs. The resulting changes in demand for agricultural output are quite small, which in turn results in tiny impacts on land and water resources as well as GHGs, see Table B3. Equally, as expected, there are global welfare gains. As we consider such as “free lunch” as rather unlikely, we only discuss detailed outcomes for the two other scenarios in the following.

Considering the non-cost neutral scenario with adjustment cost, Figure 1 shows the impact on value added of the food processing industry. The map suggests some tiny losses (up to 0.07%) in the Southern Member States, France, Sweden, parts of the Baltics and Eastern Europe, while some regions would experience small positive changes (up to 0.9%). We have ascertained that most of the reductions in the value added are driven by export contraction. Figures B7 and B8 in the annex shows changes in agricultural value added. The largest decreases are in the animal production industries, with drops ranging from 1.7% up to 3.4%. These reductions mostly reflect lower intermediate demand by the food processing industries. As explained before, the reduction in demand for crop products is smaller, ranging from -1.6% to -0.5%.

Interestingly, there is a small rise in the global demand for processed food in both scenarios (Table 1). This is due to the increased competitiveness of the food industry, which reduces its production costs per unit of output. This has some implications in terms of food security, as even in many developing countries some staple foods, such as bread, stem from food processing.

Figure 1. Changes in value added of processed food sectors for NUTS2 regions



Source: model results (non-cost neutral scenario)

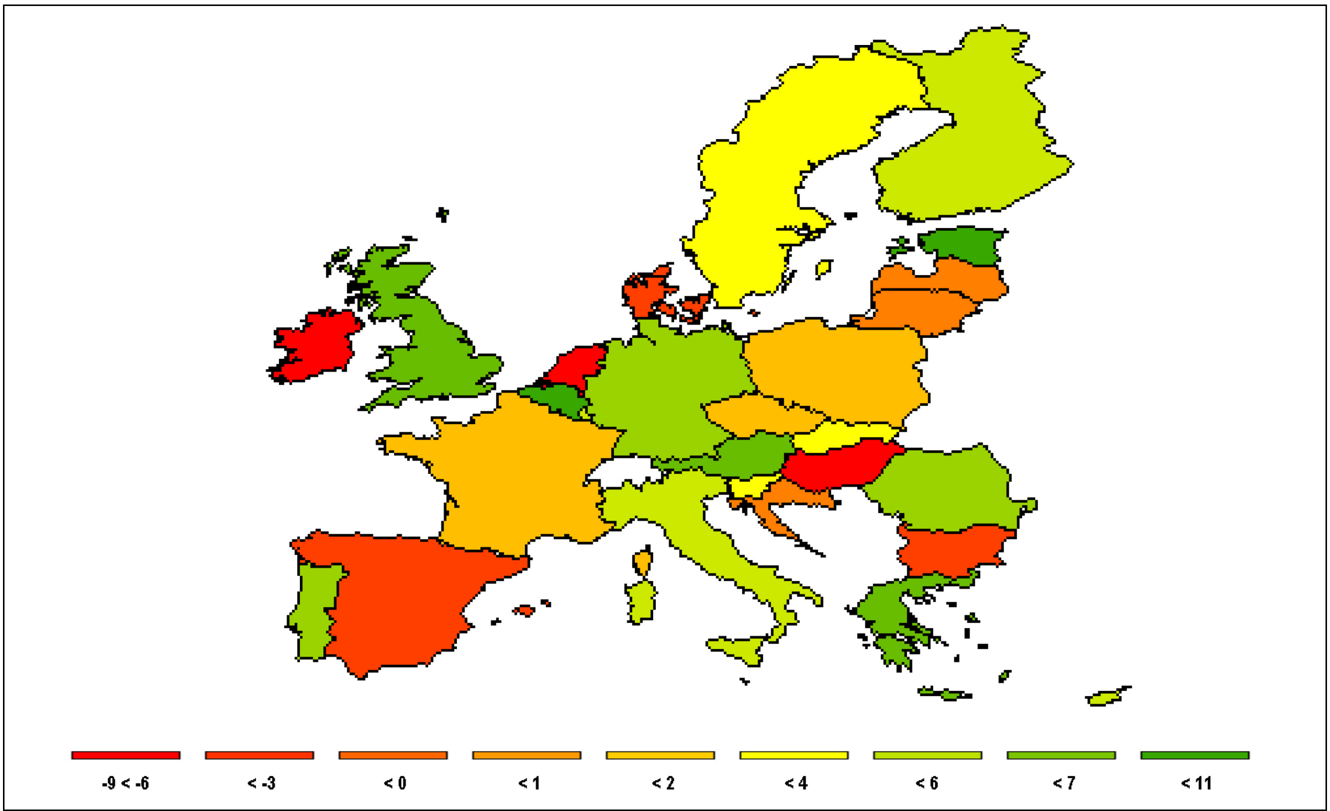
We also measure welfare impacts due to the changes in the market conditions. Our welfare measure is based on the Equivalent Variation (EV) criterion, i.e., the amount of income to be added to the regional household' benchmark income at benchmark prices to reach the same utility as under simulated income and prices. Global welfare drops very slightly, with a purchasing power loss of around \$0.1 per capita. The welfare losses for the EU are, of course, more pronounced but still small with around \$2 per capita which reflects the positive impacts of a higher value added of the food processing sectors at decreased prices and lower farm incomes (Table 1). Welfare decomposition (not shown here) suggests that the welfare loss mostly reflects reduced agricultural income, mainly resulting from lower returns to land.

These losses do not vary much across the EU member states (Figure 2). However, the direction of changes in general could be explained by the ratio of processed food output to primary agricultural output. The countries with the relatively higher ratio (4 and above) (the UK, Belgium, Italy, Portugal, Germany, Austria, Sweden and Estonia) tend to benefit, while the countries with the relatively lower ratio (Netherlands, Denmark, Hungry, Spain, Bulgaria, Ireland and France) tend to lose. These results are consistent with our result presented earlier, where the welfare loss due to reduction in agricultural output outweigh the benefits generated from the processed food sector. Our analysis does not monetarize changes in environmental status and misses changes in environmental indicators, besides GHG emissions, where benefits from reduced and less intensive agricultural production could be expected from, for example, a reduction in nitrogen and phosphorous loads.

5.2 Impact on Land Use Change

As the demand for land decreases in both scenarios because of reduction in demand for primary agricultural outputs (see Table 1), land rents in the EU are negatively affected in both scenarios by -3.3% and -4.2%, respectively, while they exhibit very small but positive changes in other regions of the world. The relatively higher changes in land rent compared to the small changes in land demand are reflected by the inelastic nature of land supply and its low substitution

Figure 2. Equivalent variation (US$ per capita)



Source: model results (non-cost neutral scenario)

elasticity. Nonetheless, significant differences in land rent changes are observed across the European regions. For example, in the non-cost-neutral scenario (Figure 3), land rent changes by -0.1% in some regions of Finland, Sweden, Italy and Southern France, but by -7% in some regions of Portugal, the UK, Germany, Ireland, Denmark, Estonia, Latvia and Lithuania. The magnitude of changes is largely explained by the magnitude of the reduction in animal and crop production illustrated in figures B7 and B8.

The most obvious impact on global land use is a change in pastureland (grazing), as can be seen from Figure 4. Indeed, as the EU's ruminant production and output of red meat drops (see Figure B8), the ROW expands pasturelands.

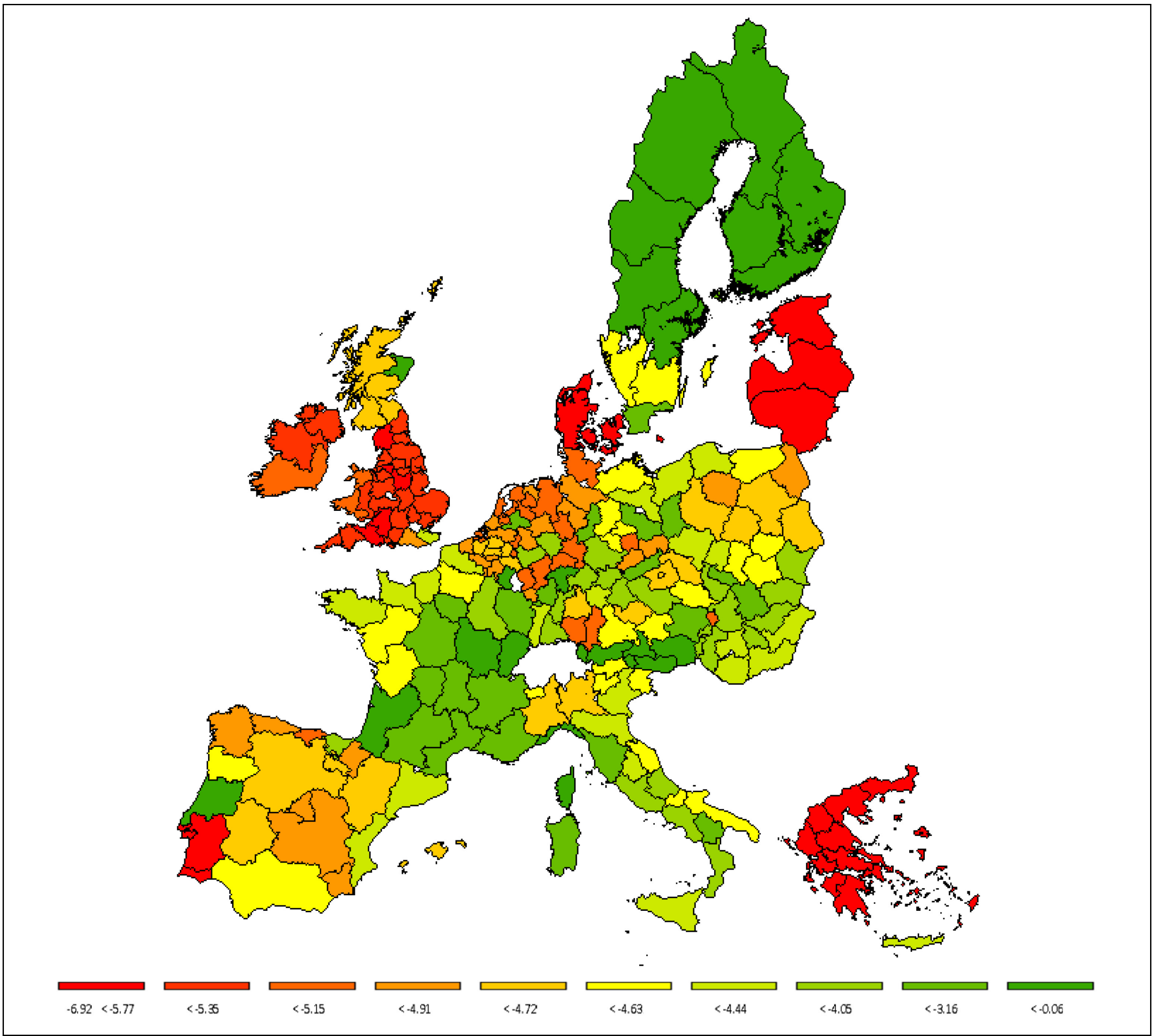
Croplands tend to expand (Figure 5), especially in the EU, where drops in animal production are larger compared to the reductions in food production (Figures B7 and B8). The expansion in cropland is driven by the decrease in pastureland that triggers substitution toward croplands (see Figure B6). In some regions such as Australia, South America and North America, the increase in pastureland may also reduce areas used for crop production.

Finally, the differentiated impact of a unilateral effort by the EU to reduce food waste can be seen from the change in managed forest areas (Figure 6). In the EU, reduced demand for agricultural products releases crop and pasture land, bringing about some afforestation in the long run. Of course, the opposite is true outside the EU, where pressure on the tropical rainforest would increase.

5.3 Impact on Water Resources

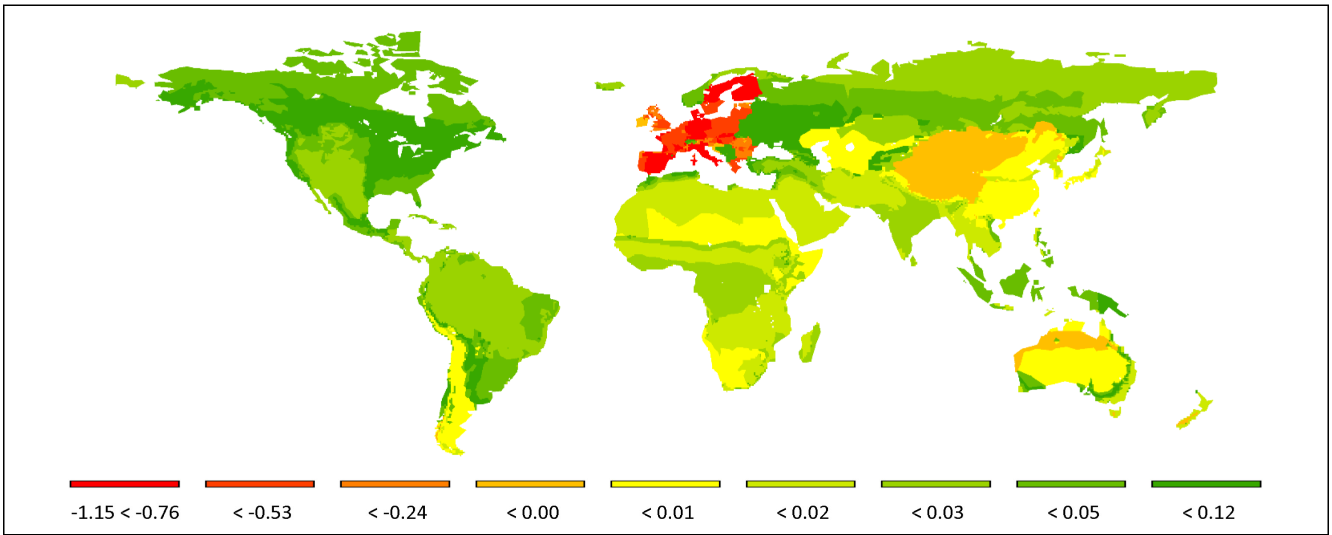
Usage of water resources in the EU decreases by 0.19 %. The largest reductions are observed in Sweden, Ireland, Poland, Slovakia and Romania. However, the use of water resources in other regions of the world increases, resulting in a negligible although positive change in a net global water use (Figure 7).

Figure 3. Percentage change in agricultural land rents



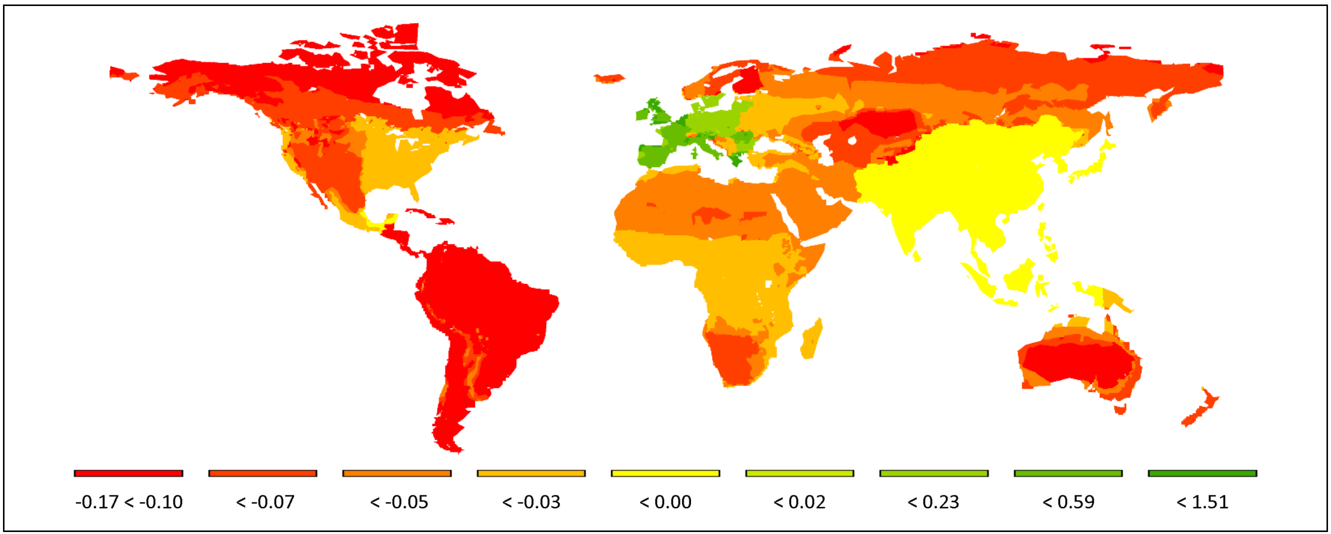
Source: model results (non-cost neutral scenario)

Figure 4. Percentage change in pastureland cover



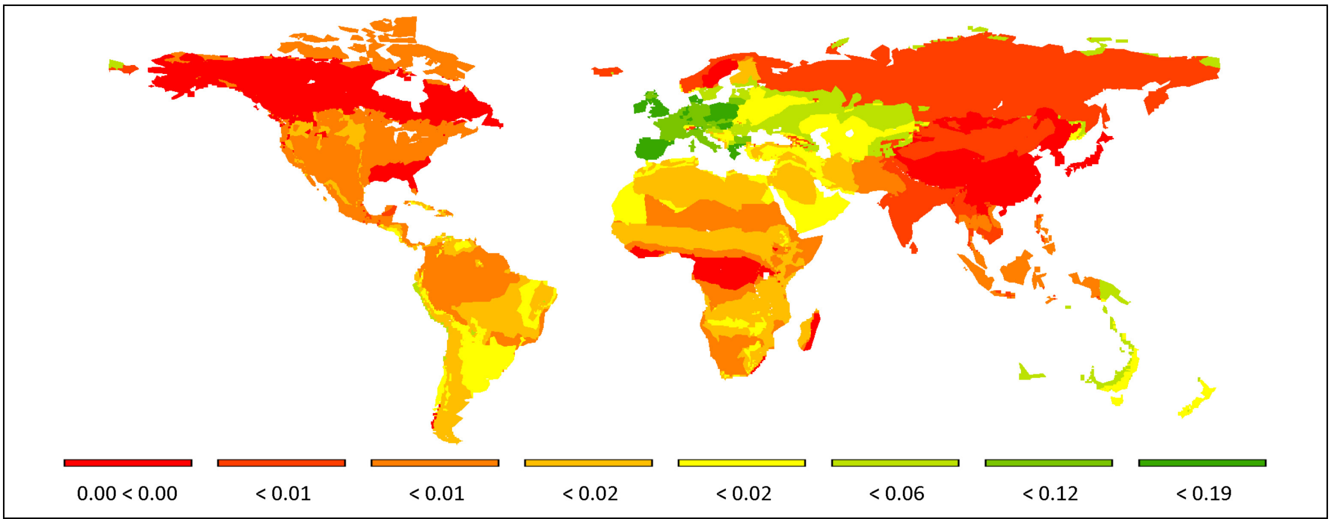
Source: model results (non-cost neutral scenario)

Figure 5. Percentage change in cropland cover



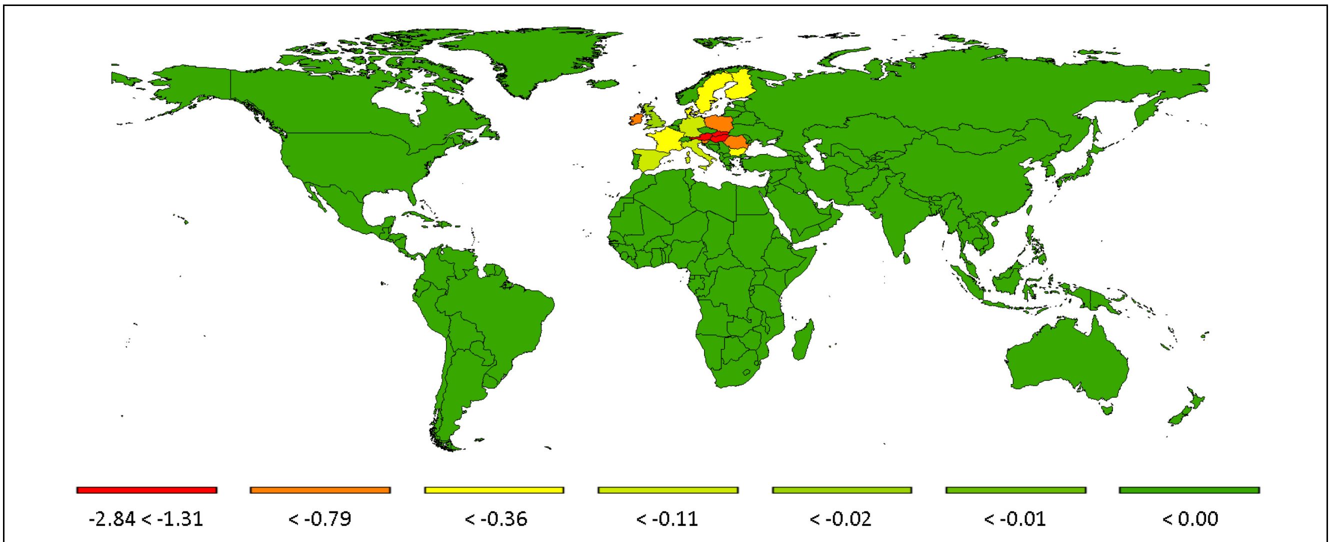
Source: model results (non-cost neutral scenario)

Figure 6. Percentage change in managed forestland cover



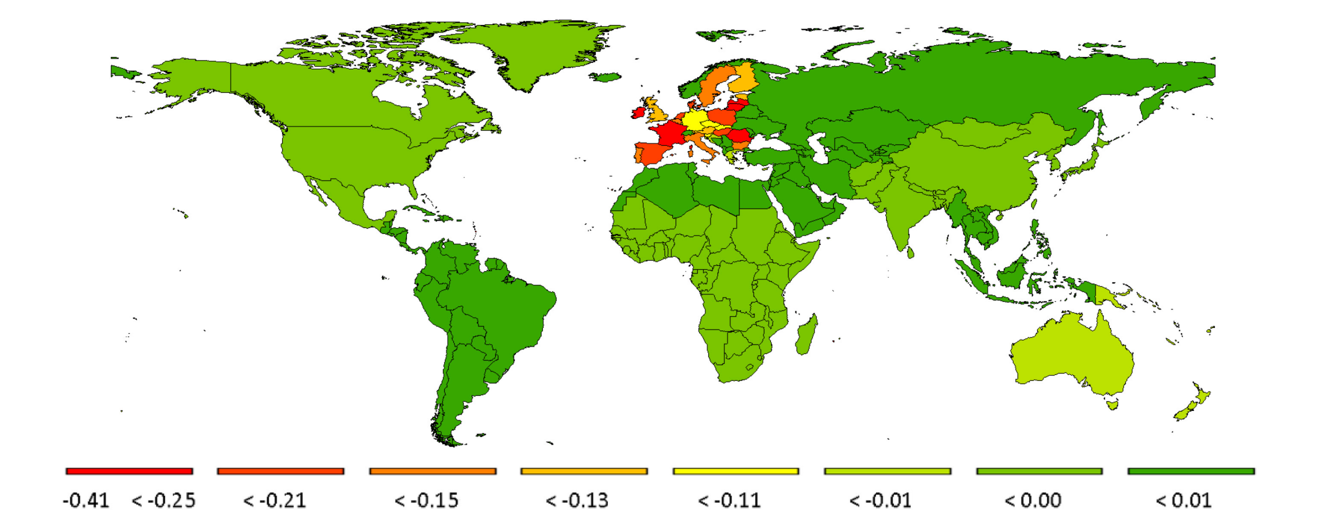
Source: model results (non-cost neutral scenario)

Figure 7. Percentage change in the use of water resources



Source: model results (non-cost neutral scenario)

Figure 8. Percentage change in CO_2 and non-CO_2 emissions [CO_2 equivalent]



Source: model results (non-cost neutral scenario)

5.4 Impact on GHG Emissions

As shown in Figure 8, no significant impact is expected for GHG global emissions. Within the EU, the reduced methane emissions from ruminant animals are compensated by higher emissions from fossil fuel use, leading to a minor net reduction across the EU of 0.4%. Under non-cost neutrality, the largest reductions in emissions are observed in Spain, France, Latvia and Slovakia. However, the net reduction in EU emissions comes at the expense of the same net increase in emissions outside the EU, leaving no significant reductions in global emissions. We also simulated a more ambitious food waste reduction scenario (10% reduction in food waste in line with the EU target of 50% reduction in food waste) to further explore the sensitivity of GHGs to food waste reduction policies. This results in an additional 0.25% reduction in GHGs, leading to cumulative reduction of 0.65% reduction in GHGs. The main reasons behind these small changes are that food waste constitutes a small proportion (3%) of total GHG emissions (MONIER et al., 2010) and that most of the reduction in CO_2 emissions due to food waste reduction technology will be compensated by the CO_2 emitted in the production of intermediate inputs that will be used elsewhere.

6 Policy Recommendations and Caveats

Our analysis shows that reduced food waste in Europe has only limited impacts on food availability in regions such as Sub-Saharan Africa, despite the far-reaching integration of global agricultural and food markets. There are multiple reasons for this. Firstly, the reduced demand for agricultural products in Europe leads to price decreases, which lead to reduced supply in Europe and beyond. That implies that a ton less food waste does not imply a ton more food available in the market. Secondly, assuming that reducing food loss comes at a cost, the average cost for processed food would increase.

We thus conclude from our findings that costly efforts to reduce food losses in Europe cannot be motivated in terms of significant contributions to global food availability or environmental benefits. That does not mean that policy interventions should be abandoned, but they should rather focus on targeted actions, reducing losses at low cost or reducing consumption of products with a high environmental footprint. Furthermore, if the existence of market failures and public goods are brought into the picture, a broader scope for policy intervention would emerge and aggregate welfare effects would be somewhat more on the positive side. Nonetheless, we believe that considerations about the "possible" or "likely" existence of market failures are not sufficient to support food waste reduction policies. Rather, market failures and externalities should be properly identified and quantified. However, this kind of analysis goes beyond the scope of this work.

Our findings suggest that consideration of adjustment costs matter: the increase of food availability from less food waste is reduced along with pressure on natural resources, such as land and water, as agricultural production drops compared to a "free lunch" assumption. However, considering adjustments costs or not lead to similar GHGs saving. Higher saving of GHGs in the scenarios that consider adjustment costs are compensated by the induced emissions from the higher use of non-agricultural intermediate inputs.

It should be noted 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.

How would one model compensatory costs? 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 model, but this would go beyond the scope of this work. Therefore, the chosen solution is proportional scaling of other production factors, which may not be very realistic but at least has the merit of not introducing additional and somehow arbitrary distortions in the simulation experiments.

One could also notice that this research has focused on the food processing industry alone, which accounts 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) and STENMARCK et al. (2016)). Although two studies on food waste at the household level do exist (BRITZ et al., 2014, and PHILIPPIDIS et al., 2019), the point we want to make here is that most of the methodology and approaches 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 higher consumption of other items.

As it is often the case with numerical exercises, such as the one described in this paper and despite the fact that we have made use of a rich and detailed data set, the quality of data remains a critical aspect, along with the assumptions about behavioural parameters, such as substitution elasticities. Consequently, we are aware that our numerical estimates are subject to various degrees of uncertainty. Nonetheless, the overall qualitative picture and the key insights emerging from our numerical simulations are robust to alternative defined scenarios and therefore, provide useful guidance for policies in this field.

7 Conclusion

Food waste is a serious challenge across globe. The European Commission already addressed this challenge by targeting the reduction of food waste to half of its business as usual level by 2030. This study, for the first time presents a comprehensive analysis of the impact of a reduction in food waste in the EU on food availability, natural resources (i.e. water and land use change) and the environment within and outside the EU. Contrary to the literature that assigns no adjustment cost to reduce food waste, this study departs from this assumption. Accordingly, we simulate food waste reduction in food processing sectors under two different assumptions with regard to the cost of food waste: first, assuming that the costs of reducing food waste are equal to the monetary savings for the food processing industry and, second, by assuming that the costs of reducing food waste are twice as much as the savings from food waste. The scenarios assume a food waste reduction in the food industry that is equal to 5% of the intermediate input use of food processing sectors.

For the purposes of this study, we employ a CGE model that covers a global economy with the EU at the NUTS 2 resolution, while considering the detailed representation of agriculture and food production sectors, agro-ecological land use resolutions, irrigation water as a primary factor of production and the direct and non- direct CO_2 emissions. Our result shows that consideration of adjustment costs matters. Higher adjustment costs are likely to result in smaller increase in food availability and larger reduction in primary agricultural production and use of natural resources. Moreover, we confirm that a unilateral commitment of the EU to reduce food loss and waste is likely to decrease the competitiveness of the EU food processing sector. Reduced demand for primary agricultural inputs would shrink the EU's agricultural sectors, applying pressure to farm incomes and land prices. The contribution to global food security would be minor, as the adjustments would be concentrated in the 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 water and land resources and emissions relevant for climate change at the global level and only very limited impact inside the EU. We note that our results are driven by the specific assumptions used in the general equilibrium model, which do not consider the possible existence of externalities and public goods. We conclude from the findings that costly efforts to reduce food loss in Europe cannot be motivated by large contributions to improved global food availability or environmental status. That does not mean that policy interventions should be abandoned, but there is a need for global coordination of food waste reduction policies. Policies in the EU should focus on targeted actions which reduce losses at low costs and focus on products with a high environmental footprint.

References

BAGHERZADEH, M., M. INAMURA and H. JEONG (2014): Food waste along the food chain. OECD Food, Agriculture and Fisheries Papers 71. OECD Publishing, Paris.

BAHADUR, K.K.C., I. HAQUE, A.L. LEGWEGOH and E.D.G. FRASER (2016): Strategies to reduce food loss in the global south. In: Sustainability 8 (7):1-19.

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

BERETTA, C., F. STOESSEL, U. BAIER and S. HELLWEG (2013): Quantifying food losses and the potential for reduction in Switzerland. In: Waste Management 33 (3): 764-773.

BETZ, A., J. BUCHLI, C. GUEBEL and C. MUELLER (2015): Food waste in the Swiss food service industry-Magnitude and potential for reduction. In: Waste Management 35 (2015): 218-226.

BRITZ, W. (2017): CGEBox - a flexible and modular toolkit for CGE modelling with a GUI. University of Bonn. Available at: http://www.ilr.uni-bonn.de/em/rsrch/cgebox/cgebox_GUI.pdf, last accessed 25 September 2018.

Britz, W., H. DUDU and E. FERRARI (2014): Economy-wide impacts of food waste reduction: a general equilibrium approach. Conference paper EAAE, Ljubljana, 2014.

BRITZ, W., H. DUDU., F. ILARIA, Y. JAFARI, R. ROSON, S. LUCA and M. SARTORI (2019): Economy-wide analysis of food waste reductions and related costs. JRC Technical Reports. DOI: 10.2760/942172

BRITZ, W. and D. VAN DER MENSBRUGGHE (2018): CGE-Box: A flexible, modular and extendable framework for CGE analysis in GAMS. In: Journal of Global Economic Analysis 3 (2): 106-176.

BRITZ, W. and P. WITZKE (2012): CAPRI model documentation 2012. University Bonn. Available at www.capri-model.org.

CALDEIRA, C., S. CORRADO and S. SALA (2017): Food waste accounting - methodologies, challenges and opportunities. JRC technical report, JRC109202. Publications Office of the European Union, Luxembourg.

CAMPOY-MUNOZ, P., M. CARDENETEA and M. DELGADO (2017): Economic impact assessment of food waste reduction on European countries through social accounting matrices. In. Resources, Conservation and Recycling 122 (2017): 202-209.

CHABOUD, G. and B. DAVIRON (2017): Food losses and waste: Navigating the inconsistencies. In. Global Food Security 12 (2017): 1-7.

ELLISON, B. and J.L. LUSK (2018): Examining household food waste decisions: A vignette approach. In. Applied Economic Perspective and Policy 40 (4): 613-631.

EUROPEAN COMMISSION (2014a): Towards a circular economy: A zero waste programme for Europe. In: https://ec.europa.eu/environment/circular-economy/pdf/circular-economy-communication.pdf, accessed 25 July 2019.

– (2014b): Impact assessment on measures addressing food waste to complete SWD (2014) 207 regarding the review of EU waste management targets. In: https://ec.europa.eu/environment/archives/eussd/pdf/IA.PDF, accessed 25 July 2019.

EUROPEAN PARLIAMENT (2018): Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste. In: http://data.europa.eu/eli/dir/2018/851/oj, accessed 25 July 2019.

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

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

– (2014a): Food wastage footprint. Full-cost accounting. Rome.

– (2014b): Food loss assessments: causes and solutions. Case studies in small-scale agriculture and fisheries subsectors. Rome.

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

– (2014d): Mitigation of food wastage societal costs and benefits. Rome.

FAO and IIASA (Food and Agriculture Organization of the United Nations and International Institute for Applied System Analysis) (2000): Global Agro-Ecological Zones – 2000. Rome, Italy, and Laxenburg, Austria.

THE FOOD LOSS & WASTE PROTOCOL (2019): Food loss and waste accounting and reporting standards. In: http://flwprotocol.org/wp-content/uploads/2017/05/FLW_Standard_final_2016.pdf, accessed 25 July 2019.

FERRARI, E., M. HIMICS and M. MUELLER (2010): WP2.2 Databases – Regional social accounting matrices deliverable: d2.2.4, procedure for the compilation of regional SAMs based on national SAMs and available regional datasets: dataset and documentation, CAPRI-RD, 2010. Available at: http://www.ilr.uni-bonn.de/agpo/rsrch/capri-rd/docs/d2.2.4.pdf, accessed 21 November 2018.

FILHO, W. L. and M. KOVALEVA (2015): Food waste and sustainable food waste management in the Baltic sea region. Springer, New York.

GIBBS, H., S. YUI and R. PLEVIN (2014): New estimates of soil and biomass carbon stocks for global economic models. GTAP Technical Paper No. 33. Centre for Global Trade analysis Project, Purdue Univesity, Indiana, USA.

HAMILTON, S.F. and T.J. RICHARDS (2019): Food policy and household food waste. In: American Journal of Agricultural Economics 101 (2): 600-614.

HAQIQI, I., F. TAHERIPOUR, J. LIU and D. VAN DER MENSBRUGGHE (2016): Introducing irrigation water into GTAP data base version 9. In: Journal of Global Economic Analysis 1 (2): 116-155.

HERTEL, T.W (1997): Global trade analysis: modelling and applications. Cambridge University Press, Cambridge, UK.

HERTEL, T.W., S. ROSE and R. TOL (2009): Land use in computable general equilibrium models: An overview. In: Hertel, T.W., S. Rose and R. Tol (eds.): Economic Analysis of Land Use in Global Climate Change Policy. Routledge, Abington, United Kingdom.

HLPE (the High Level Panel of Experts) (2014): Food losses and waste in the context of sustainable food systems. HLPE Reports series. In: http://www.fao.org/3/a-i3901e.pdf, accessed 25 July 2019.

HOJGARD, S., T. JANSSON and E. RABINOWICZ (2013): Food waste among Swedish households much ado about nothing? Working Paper No: 2013:8. AgriFood Economics Center, Lund, Sweden.

IRFANOGLU, Z.B. and D. VAN DER MENSBRUGGHE (2016): Development of the version 9 non-Co2 GHG emissions database. GTAP 9 Satellite Data and Utilities Documentation. Global Trade Analysis Project, Purdue University, Indiana, USA.

KEENEY, R. and T. HERTEL (2005): GTAP-AGR: a framework for assessing the implications of multilateral changes in agricultural policies. GTAP Technical Paper 25. Center for Global Trade Analysis, Purdue.

KOESTER, U. (2014): Food loss and waste as an economic and policy problem. In: Intereconomics- Review of European Economic Policy 49 (6): 348-354.

KUMMU, M., H.D. MOEL, M. PORKKA, S. SIEBERT, O. VARIS and P. WARD (2012): Lost food, wasted resources: Global food supply chain losses and their impacts on freshwater, cropland and fertiliser use. In: Science of the Total Environment 438 (2012): 477-489.

LEVANO, P., L. MOISES, F. TAHERIPOUR and W. TYNER (2015): Development of the GTAP land use data base for 2011. GTAP Research Memorandum No. 28. Center for Global Trade Analysis, Purdue.

LIPINSKI, B., C. HANSON, R. WAITE, T. SEARCHINGER, J. LOMAX and L. KITINOJA (2013): Reducing Food Loss and Waste. Retrieved from http://www.wri.org/publication/reducing-food-loss-and-waste.

MONIER, V., M. SHAILENDRA, V. ESCALON, C. O'CONNOR, T. GIBON, G. ANDERSON,G. MORTON (2010): Preparatory study on food waste across EU 27. Technical report-2010-054. European Commission, Brussels.

PHILIPPIDIS, G., M. SARTORI. E. FERRARI and R. M'BAREK (2019): Waste not, want not: A bio-economic impact assessment of household food waste reductions in the EU. In: Resources, Conservation and Recycling 146 (2019): 514-522.

POLIMENI, J.M., K. MAYUMI, M. GIAMPIETRO and B. ALCOTT (2008): The Jevons Paradox and the myth of resource efficiency. Earthscan, London, UK.

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

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

RUTTEN, M., P. NOWICKI, M. BOGAART and L. ARAMYAN (2013): Reducing food waste by households and in retail in the EU. LEI report 2013-035. LEI Wageningen, The Hague.

RUTTEN, M. and M. VERMA (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. LEI Wageningen, The Hague.

RUTTEN, M., M. VERMA and N. MHLANGA (2015): Potential impacts on sub-Saharan Africa of reducing food loss and waste in the European Union. FAO, Rome.

SALEMDEEB, R., D.F. VIVANCO, A. AL-TABBAA and E.K. ERMGASSEN (2017): A holistic approach to the environmental evaluation of food waste prevention. In: Waste Management 59 (2017): 442-450.

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

SOMKUN, P. (2017): Stochastic mathematical model for food waste reduction in a two-level supply chain for

highly perishable products. In: International Journal of Supply Chain Management 6 (1): 165-171.
STENMARCK, A., C. JENSEN and T. QUESTED (2016): Estimates of European food waste levels. FUSIONS Project Report, Stockholm.
TEUBER, R. and J.D. JENSEN (2016): Food losses and food waste: extent, underlying drivers and impact assessment of prevention approaches. IFRO Report No. 254. Department of Food and Resource Economics, University of Copenhagen.
TONINI, D., L.K. BROGAARD and T.F. ASTRUP (2017): Food waste prevention in Denmark. Identification of hotspots and potentials with life cycle assessment. Danish Environmental Protection Agency, København K.
UNITED NATIONS (2015): Resolution adopted by the General Assembly on 25 September 2015. Transforming our world: the 2030 Agenda for Sustainable Development. In: https://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E, accessed 26 July 2019.
USDA (2018): US food waste challenge. In: https://www.usda.gov/oce/foodwaste/faqs.htm, accessed 25 July 2019.
VAQUE, L.G. (2015): Food loss and waste in the European Union: A new challenge for the food law? In. European Food and Feed Law Review (1/2005): 20-33.
VAN DER WERF, P. and J.A. GILLILAND (2017): A systematic review of food losses and food waste generation in developed countries. In: Waste and Resource Management 170 (2): 66-77.
VAN DER MENSBRUGGHE, D. (2018): The Standard GTAP model in GAMS, Version 7". In: Journal of Global Economic Analysis 3 (1): 1-83.
VENTOUR, L. (2008): The food we waste. WRAP report. WRAP, London. In: http://www.lefigaro.fr/assets/pdf/Etude%20gaspillage%20alimentaire%20UK2008.pdf, accessed 25 July 2019.
WRAP (the Waste and Resources Action Programme) (2009): Household food and drink waste in the UK. WRAP report, London. In: http://www.wrap.org.uk/sites/files/wrap/Household_food_and_drink_waste_in_the_UK_-_report.pdf, accessed 25 July 2019.
XUE, L., G. LIU, J. PARFITT, X. LIU, E. VAN HERPEN and S. CHENG (2017): Missing food, missing data? A critical review of global food losses and food waste data. In. Environmental Science and Technology 51 (12): 6618-6633.

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Appendix A: 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, 2014a; LIPINSKI et al., 2013; BCFN, 2012; FAO, 2011). Food loss is generally attributed to the earlier stages of the 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 reserve 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, 2014b; FAO, 2014c; FAO, 2011) while other authors argue that since food is diverted to animal feed, a transformation of food to livestock products, it cannot be considered 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, 2014d). Indeed, FAO (2014d) changes the former FAO definition of food waste by excluding food diverted to animal feed as food waste (BAGHERZADEH et al., 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, 2014c).
- 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 products” 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 stages as part of food waste (FAO, 2014c; HLPE, 2014) while others do not. Particularly in the US, food waste is mostly considered to be a waste management problem and the focus is on post-harvest losses and waste (USDA, 2018).

Along with the above axes, many 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 differ, along with 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. What matters more here is the percentage of food that is wasted at different stages of the FSC. 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 standpoint (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 et al., 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.

Appendix B: Supplemental Tables and Figures

Table B1. Sectoral correspondence of GTAP sectors to new sectors

No.	Code	GTAP and model sectors	Sectoral aggregation/ disaggregation	Post model aggregation
1	PDR	Paddy rice	Irrigated Paddy rice	Irrigated crop
			Rainfed Paddy rice	Rainfed crops
2	WHT	Wheat	Irrigated Wheat	Irrigated crop
			Rainfed Wheat	Rainfed crops
3	GRO	Cereal grains nec	Irrigated Cereal grains nec	Irrigated crop
			Rainfed Cereal grains nec	Rainfed crops
4	V_F	Vegetables, fruit, nuts	Irrigated Vegetables, fruit, nuts	Irrigated crop
			Rainfed Vegetables, fruit, nuts	Rainfed crops
5	OSD	Oil seeds	Irrigated Oil seeds	Irrigated crop
			Rainfed Oil seeds	Rainfed crops
6	C_B	Sugarcane, sugar beet	Irrigated Sugarcane, sugar beet	Irrigated crop
			Rainfed Sugarcane, sugar beet	Rainfed crops
7	PFB	Plant-based fibers	Irrigated Plant-based fibers	Irrigated crop
			Rainfed Plant-based fibers	Rainfed crops
8	OCR	Crops nec	Irrigated Crops nec	Irrigated crop
			Rainfed Crops nec	Rainfed crops
9	CTL	Bovine cattle, sheep and goats, horses	Bovine cattle, sheep and goats, horses	livestock
10	OAP	Animal products nec	Animal products nec	livestock
11	RMK	Raw milk	Raw milk	livestock
12	WOL	Wool, silk-worm cocoons	Wool, silk-worm cocoons	livestock
13	FRS	Forestry	Forestry	Other primary agriculture
14	FSH	Fishing	Fishing	Other primary agriculture
15	COA	Coal	Mineral extraction sectors	Mineral extraction sectors
16	OIL	Oil	Mineral extraction sectors	Mineral extraction sectors
17	GAS	Gas	Mineral extraction sectors	Mineral extraction sectors
18	OMN	Minerals nec	Mineral extraction sectors	Mineral extraction sectors
19	CMT	Bovine meat products	Bovine meat products	Processed foods
20	OMT	Meat products nec	Meat products nec	Processed foods
21	VOL	Vegetable oils and fats	Vegetable oils and fats	Processed foods
22	MIL	Dairy products	Dairy products	Processed foods
23	PCR	Processed rice	Processed rice	Processed foods
24	SGR	Sugar	Sugar	Processed foods
25	OFD	Food products nec	Food products nec	Processed foods
26	B_T	Beverages and tobacco products	Beverages and tobacco products	Processed foods
27	TEX	Textiles	Other ‘traditional’ bio-based	Manufacturing
28	WAP	Wearing apparel	Other ‘traditional’ bio-based	Manufacturing
29	LEA	Leather products	Other ‘traditional’ bio-based	Manufacturing
30	LUM	Wood products	Other ‘traditional’ bio-based	Manufacturing
31	PPP	Paper products, publishing	Other ‘traditional’ bio-based	Manufacturing
32	P_C	Petroleum, coal products	Petrochemicals	Manufacturing
33	CRP	Chemicals, rubber, plastic products	Petrochemicals	Manufacturing
34	NMM	Mineral products nec	Other manufactures	Manufacturing
35	I_S	Ferrous metals	Other manufactures	Manufacturing
36	NFM	Metals nec	Other manufactures	Manufacturing
37	FMP	Metal products	Other manufactures	Manufacturing
38	MVH	Motor vehicles and parts	Other manufactures	Manufacturing
39	OTN	Transport equipment nec	Other manufactures	Manufacturing
40	ELE	Electronic equipment	Other manufactures	Manufacturing
41	OME	Machinery and equipment nec	Other manufactures	Manufacturing
42	OMF	Manufactures nec	Other manufactures	Manufacturing
43	ELY	Electricity	Other services	Services
44	GDT	Gas manufacture, distribution	Other services	Services
45	WTR	Water	Other services	Services
46	CNS	Construction	Other services	Services
47	TRD	Trade	Wholesale and retail trade	Services
48	OTP	Transport nec	Other services	Services
49	WTP	Water transport	Other services	Services
50	ATP	Air transport	Other services	Services

51	CMN	Communication	Other services	Services
52	OFI	Financial services nec	Other services	Services
53	ISR	Insurance	Other services	Services
54	OBS	Business services nec	Other services	Services
55	ROS	Recreational and other services	Other services	Services
56	OSG	Public Administration, Defense, Education, Health	Other services	Services
57	DWE	Dwellings	Other services	Services

Table B2. Price and quantity changes for agri-food products (% change)

	Cost neutral scenario		Non-cost neutral scenario	
	Price	Quantity	Price	Quantity
Crops	**-0.9**	**-0.8**	**-1.1**	**-0.8**
Paddy rice	-1.4	-1	-1.8	-1.6
Wheat	-0.8	-0.6	-1	-0.6
Cereal grains nec	-1.1	-1.7	-1.3	-1.8
Vegetables, fruit, nuts	-1	-0.4	-1.2	-0.3
Oil seeds	-0.7	-0.2	-1.1	-2
Sugarcane, sugar beet	-1.1	-2.1	-1.4	-2.6
Plant-based fibers	-0.8	0.9	-0.9	1.2
Crops nec	-1	-1.1	-1.2	-1
Animals	**-1.1**	**-1.5**	**-1.3**	**-2.6**
Bovine cattle, sheep and goats, horses	-0.8	-1.6	-0.9	-2.9
Animal products nec	-1.1	-1	-1.3	-2.5
Raw milk	-1.3	-2	-1.6	-2.5
Wool, silk-worm cocoons	-0.4	0.5	-0.4	0.9
Food processing	**-1.2**	**1.1**	**-0.2**	**0.2**
Bovine meat products	-2	2.2	-0.2	0.3
Meat products nec	-2.4	2.3	-0.3	0.3
Vegetable oils and fats	-2.3	3.5	-0.5	0.8
Dairy products	-1.5	1.3	-0.3	0.5
Processed rice	-1.3	0.9	-0.2	0.1
Sugar	-1	0.9	-0.2	0.2
Food products nec	-0.9	0.6	-0.1	0
Beverages and tobacco products	-0.7	0.5	-0.1	0.1

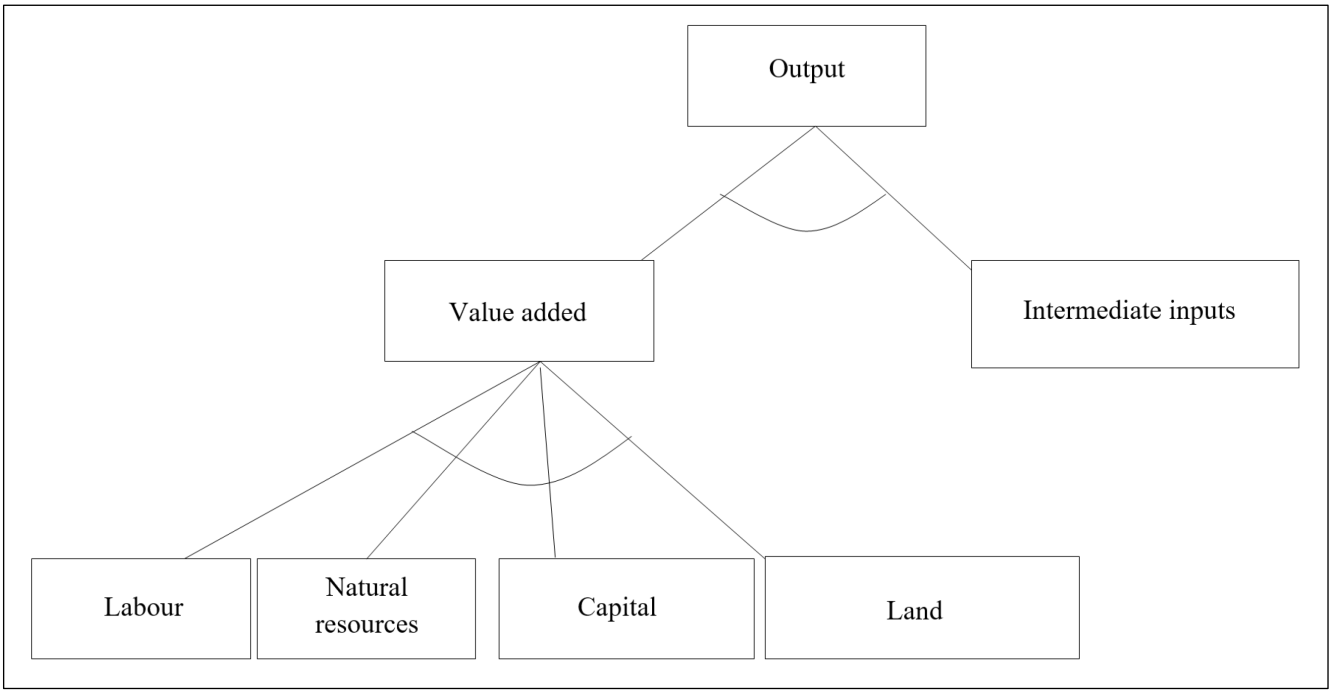
Source: model results

Table B3. Changes in agri-food markets and related environmental impacts (% change)

	Non-cost *neutral* scenario (5 percent)	
	EU	Global
Price of crops	-1.6	-0.3
Price of animals	-1.6	-0.4
Price of processed food products	-1.5	-0.5
Value added in processed food sectors	1.8	0.3
Value added in crop production	-0.2	0.1
Value added in animal production	-0.4	0.1
Land demand	-0.01	0.00
Water demand	-0.09	0.00
Farmers income	-0.2	0.05
Food consumption	0.49	0.09
Welfare	10	4

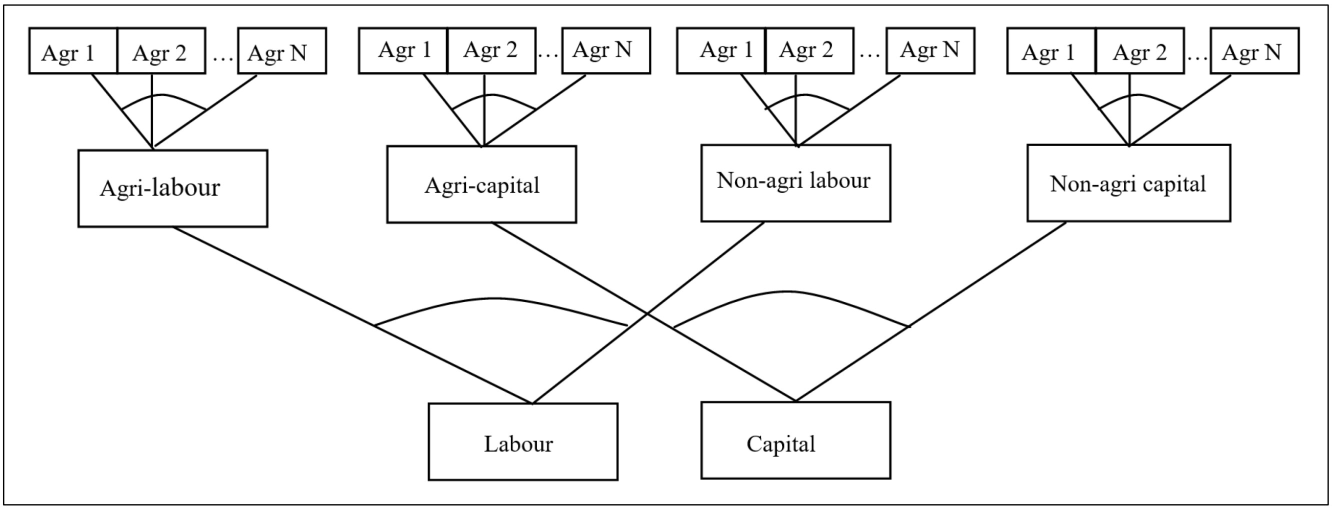
Source: model results

Figure B1. Production structure of GTAP



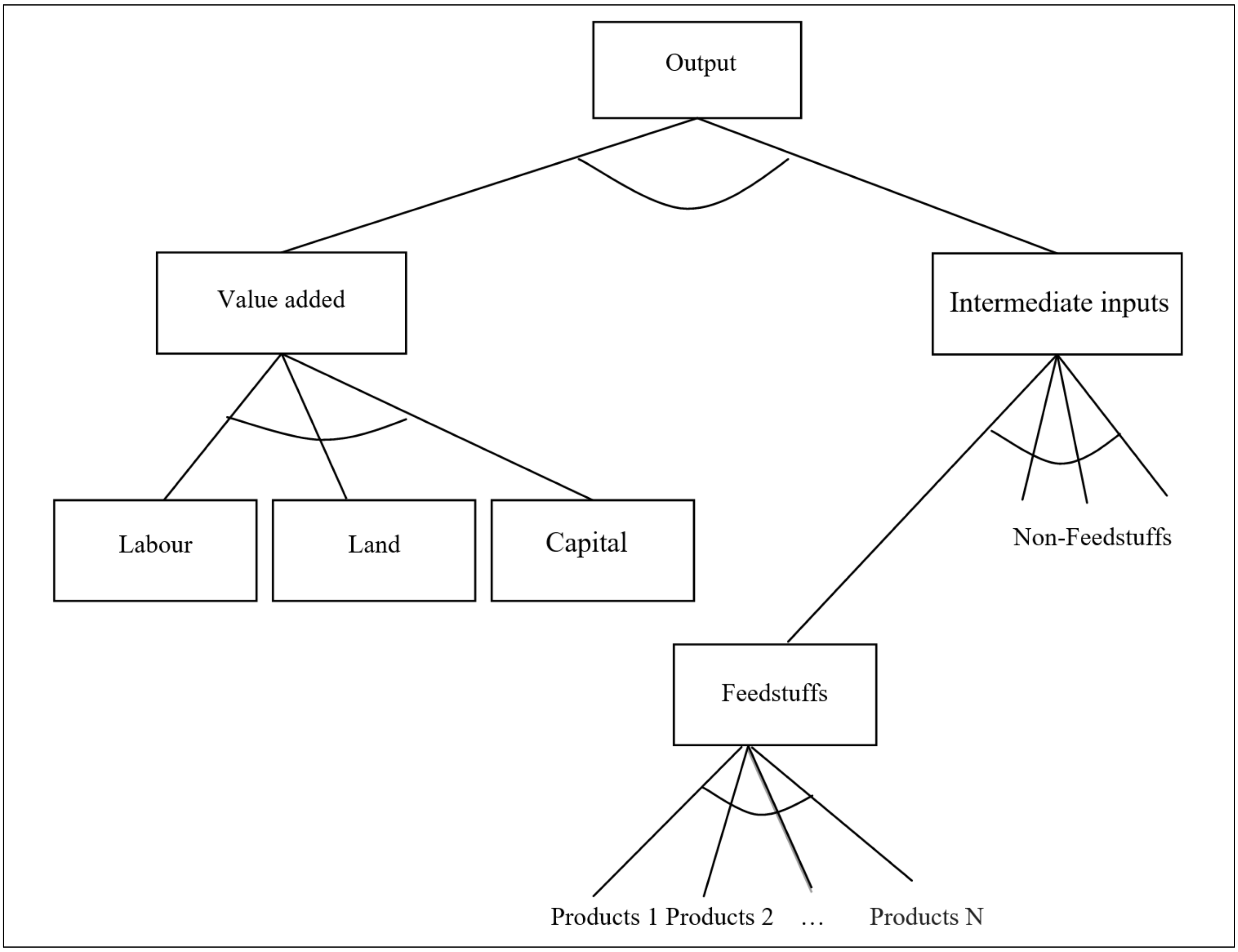
Source: HERTEL (1997)

Figure B2. Primary factors supply in GTAP-AGR



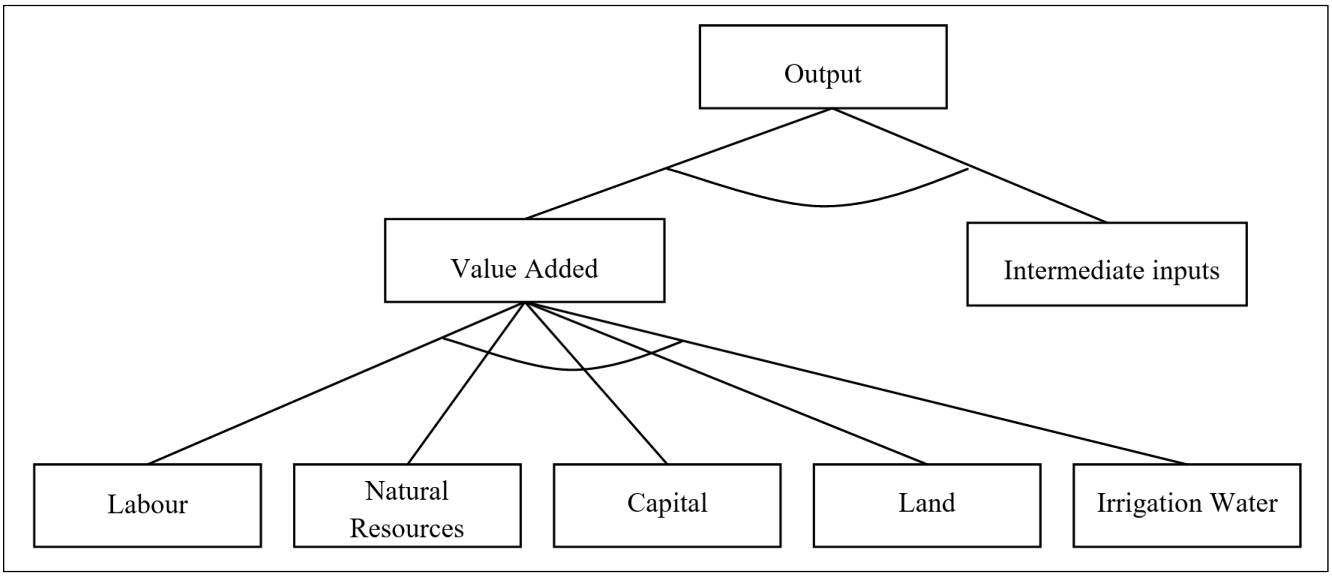
Source: authors' illustration based on KEENEY and HERTEL (2005)

Figure B3. Production structure of GTAP-AGR



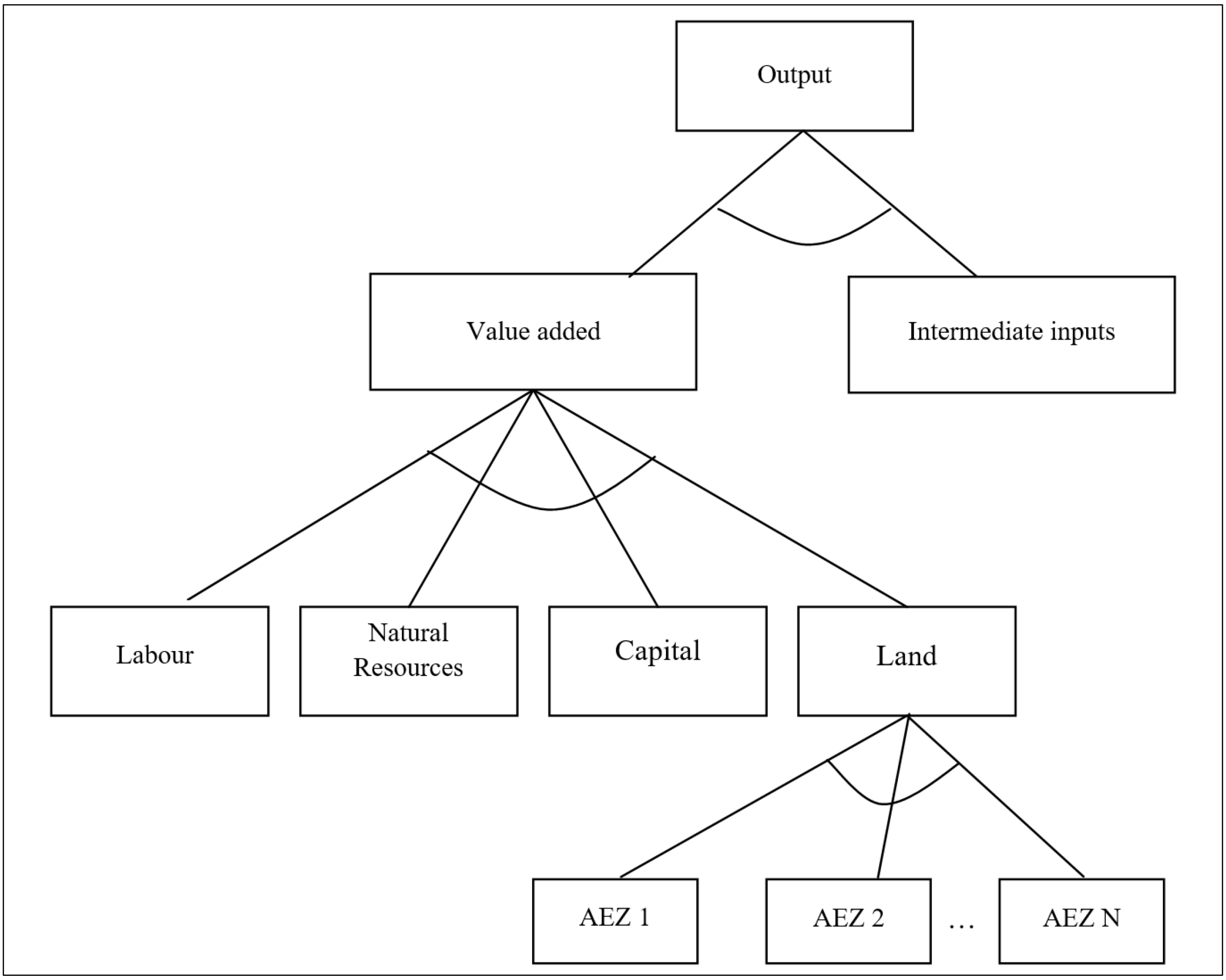
Source: KEENEY and HERTEL (2005)

Figure B4. Water as explicit primary factor in production structure



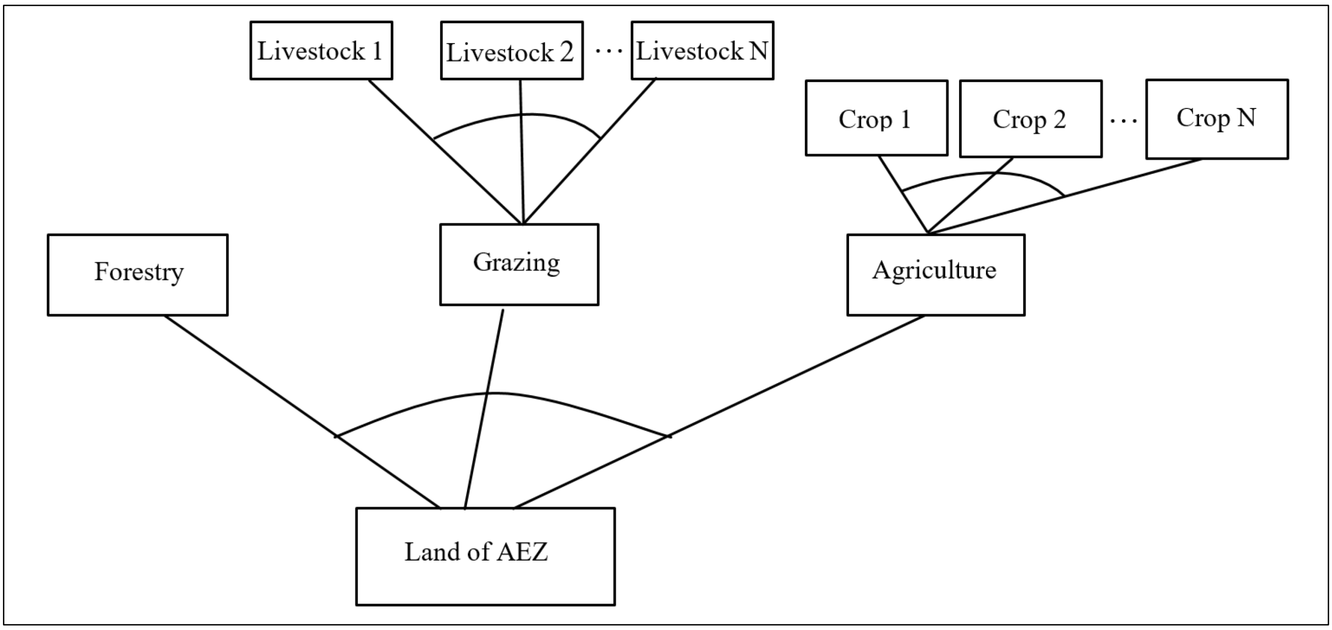
Source: authors' illustration based on HAQIQI et al. (2016)

Figure B5. Production structure of GTAP-AEZ



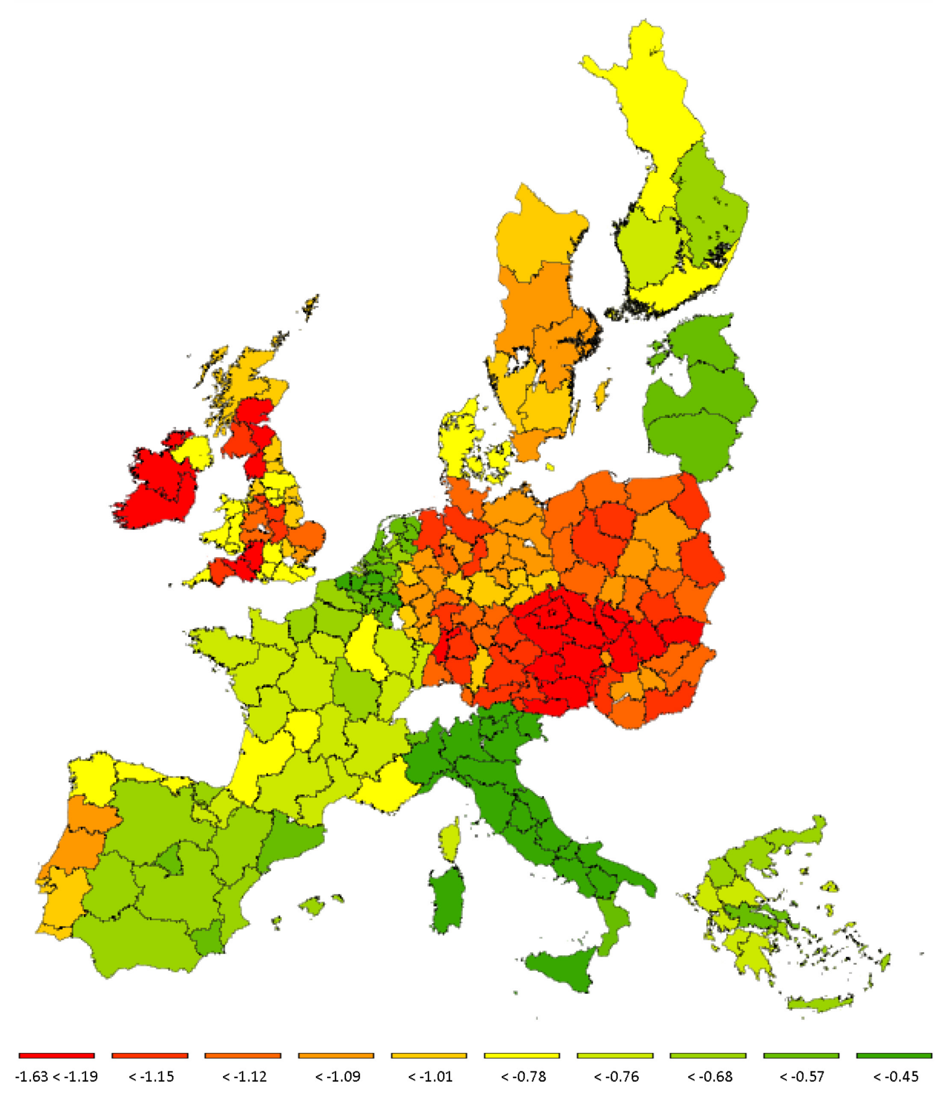
Source: HERTEL et al. (2009)

Figure B6. Land supply in GTAP-AEZ model



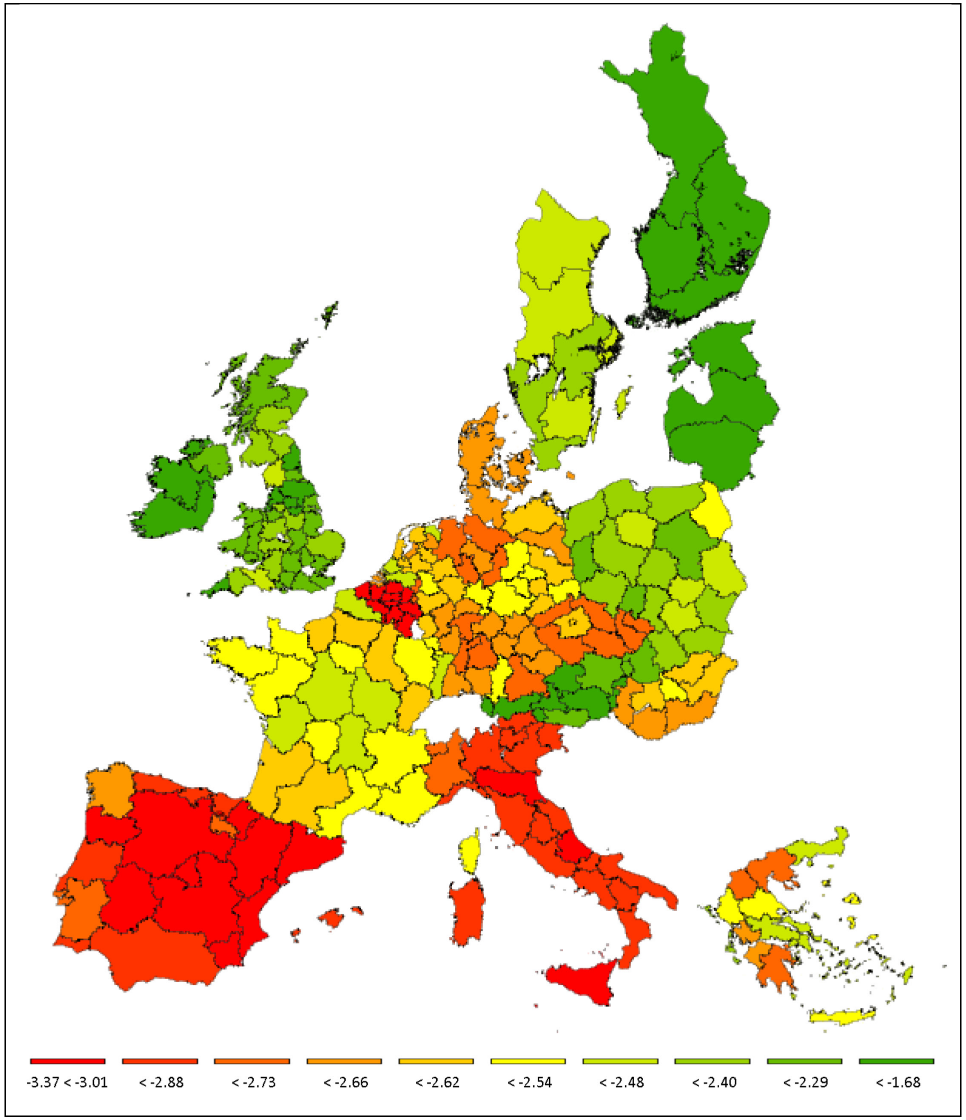
Source: HERTEL et al. (2009)

Figure B7. Change in value added for crop production



Source: model results (non-cost neutral scenario)

Figure B8. Change in value added for animal production



Source: model results (non-cost neutral scenario)