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Rebound effects of food waste prevention: Environmental impacts

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ABSTRACT

Food waste prevention across the food supply chain has been addressed by the European Union (EU) as the top priority to reduce farm-to-fork impacts. Despite the environmental benefits of food waste prevention are widely acknowledged, life cycle assessments usually do not account for rebound effects, the inclusion of which may decrease or even cancel out the expected environmental savings. Rebound effects are understood as the re-spending of accrued monetary savings, determined by the implementation of food waste prevention initiatives, either on the same product (i.e. direct effects - food) or on other products and/or services (i.e. indirect – non-food) including economy-wide effects (macroeconomic rebound effects). Macroeconomic rebound effects were quantified by means of the global equilibrium model Fidelio and were then converted into environmental impacts by performing an environmentally extended input–output analysis based on the assessment method Environmental Footprint 3.0. From an environmental and an economic perspective, it was found that food waste prevention initiatives across the entire food supply chain were beneficial, but efforts targeting households should be prioritised as the largest potential savings were obtained at this stage. Prevention initiatives implemented at households were associated with potential savings of up to 1 t CO_2-eq. t^{-1}, which was reduced to a potential saving of 0.6 t CO_2-eq. t^{-1}, corresponding to a 38 % decrease, when accounting for macroeconomic rebound effects. Finally, our results highlighted the importance of accounting for adjustment costs in the production stages of the food supply chain.

1. Introduction

Food waste represents loss of resources and environmental emissions, annually corresponding to about 8 % of global greenhouse gas (GHG) emissions (Gustavsson et al., 2011; World Bank, 2020). Tackling food waste is a critical step towards sustainability (Sánchez López et al., 2020). According to the food waste hierarchy, indicating the most and least preferred management strategies, prevention has highest priority due to large environmental benefits as demonstrated by life cycle assessments (for example, Tonini et al., 2018, Gentil et al., 2011; Oldfield et al., 2016). Very few of those studies, however, include the economic ramifications of food waste prevention (e.g. Salemdeeb et al., 2017). In this respect, an element of concern is the possibility of so-called rebound effects.

In this context, rebound effects relate to the fact that preventing food waste may free up economic resources. When those resources find a new use in production and consumption, associated environmental impacts are inevitable. These impacts may offset – and even counterbalance – the environmental benefits obtained by avoiding food waste. Such rebound effects may arise in several ways (Sorrell and Dimitropoulos, 2008). For example, with food supply chains (FSCs) less wasteful it is possible that lower prices lead to an increase in the consumption of food itself (direct rebound effect). Conversely, freed economic resources may be used on commodities other than food (indirect rebound effect). More generally, any substantial decline in food waste is likely to affect prices beyond food products triggering a variety of adjustments in the economic system (economy-wide effects). The effect of the three mentioned rebound effects results in a macroeconomic rebound effect. As such, a variety of economic effects can arise from initiatives to reduce waste across the FSC (for details, see e.g. de Gorter et al., 2021).

Several studies have attempted quantifying the economic effects of food waste prevention in the European Union (EU), usually including estimations of GHG savings. As analysed by Höjgård et al. (2013), a possible solution for lowering food waste is the inclusion of taxes

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proportional to the GHG intensity of food production. However, this proved not to be sufficient to reduce the agriculture's negative impact on the environment. Further, as discussed in Höjgård et al. (2013), the implementation of a tax would not lead to any technical improvements with the larger share of the costs borne by consumers causing a reduction in demand due to higher prices, affecting the entire economy. On the other hand, lower prices would be observed if the demand for all foods was reduced (resulting in food waste reduction) causing a fall in food import and a rise in food export from the EU. Yet, if the costs for achieving such an increase in consumption efficiency are not included, unrealistic scenarios can arise. It is therefore important to consider adjustment costs, i.e. the costs of implementing prevention initiatives, despite being difficult to estimate (Jafari et al., 2020). For example, in Philippidis et al. (2019), adjustment costs varying between 1 % and 5 % were assumed on the supply side, while in the study by European Commission (2014) a cost of 17 € t^{-1} for the implementation of prevention campaigns was employed. Yet, both in the study by Philippidis et al. (2019) and European Commission (2014), it was not investigated how consumers' savings, arising from food waste prevention, would be spent, which highly affects the results. This was analysed by Salemdeeb et al. (2017), where the impact of microeconomic rebound effects (i.e. not accounting for the three effects) was assessed. The authors estimated that the inclusion of direct and indirect rebound effects lowered GHG savings by 23–59 %, where the lower boundary reflects purchase/investment in products/services with lower GHG intensities (e.g. education or health) than food production, and the upper boundary reflects higher GHG intensity products/services (e.g. air travel). In the worst case, if savings are spent on highly polluting activities, there is the possibility of "backfire" effects, namely situations when the benefits of food waste prevention are outweighed by the re-spending of consumers (Martinez-Sanchez et al., 2016).

From the literature analysed, two main gaps were identified: i) the quantification of macroeconomic rebound effects including price elasticities and cross-elasticities of food and non-food goods; and, ii) the assessment of the environmental impacts associated with rebound effects across all relevant impact categories to avoid burden shifts (Sala et al., 2021). In this study, we first utilise a general equilibrium model of the economy, Fidelio 3 (Rocchi et al., 2019), to simulate changes in production and consumption under various food waste prevention scenarios. Secondly, the results of the economic simulations are combined with the environmental extensions of the Exiobase 3 input–output database (Merciai and Schmidt, 2018) to quantify the associated environmental pressures. Following the approach in Beylot et al. (2019), the environmental pressures were paired with up-to-date impact assessment models to quantify a wide range of different environmental impacts and, therefore, avoid burden-shifts. The results from this analysis are provided as guidance to policy- and decision-makers for identifying where in the FSC initiatives can be applied to achieve most benefits.

2. Materials and methods

In the study, we defined scenarios focusing on the economic and environmental effect of decreasing food waste levels (i.e. shock) to the ones set by the reduction targets proposed by the ongoing policy debate (Section 2.4). The corresponding economic effects were estimated by using Fidelio, while the environmental impacts were quantified by means of an input–output life cycle assessment (Section 2.1–2.3).

Rebound effects need to be included, especially in consequential LCAs where consequences of policies/implementation of technologies/etc. are anticipated to be significant. Typically, this is the case when the cost difference between scenarios analyzed is important (e.g. between incineration and landfill the cost difference may be around 20–40 euro; between prevention and incineration can be thousands of euro; this generates income changes and rebounds). These will have effects also on other sectors in the economy and on households. However, in most cases, rebound effects are minor and can therefore be neglected in the analysis. Combining LCAs with economic models is the only avenue to be able to calculate the impacts outside of a product/system's life cycle (Earles et al., 2013). Both the economic and the environmental assessment can be performed in different ways. Indeed, the former can be carried out through a computable equilibrium model (either partial or global) or through income distribution models (Almeida et al., 2022), while the latter can either be performed through top-down or process-based LCAs. Among the others, Dandres et al. (2011) and Earles et al. (2013) propose to pair computable equilibrium models together with process-based LCAs, while Almeida et al. (2022) performed a top-down LCA by means of Exiobase. We believe that combining the results of economic models with input–output tables, such as the ones reported in Exiobase, is the most straightforward way of accounting for the environmental impacts of rebound effects in the economy. It is important to note that the results obtained with such an LCA should not be directly compared with results obtained from bottom-up LCAs, but should be rather used to complement bottom-up LCAs, which typically exclude rebounds.

2.1. Food waste in the economy

The global economy is divided into a certain number, K, of geographical regions. The production side of the economy consists of I industries. Let q_{ik} represent the output of industry i in country k, for $i = 1,\ldots,I$, and $k = 1,\ldots,K$. On the consumption side, households allocate their budget among J consumption categories. The quantity of category j products purchased by region k households will be denoted b_{jk}. As customary in this family of models, production and consumption choices reflect profit- and utility-maximizing behaviour, respectively.

Waste is introduced in the analysis using an approach similar to that of de Gorter et al. (2021). We assume that part of the economy's output disappears (at no cost) before it can be sold. The rate at which output is lost in industry i in region k will be designated as ω_{ik}. This leaves $u_{ik} = (1\text{-}\omega_{ik})q_{ik}$ units of available output, with $0 \leq \omega_{ik} \leq 1$ for all i's and k's. Similarly, we postulate that households actually consume only a portion of the goods they purchase. Quantities consumed and purchased are related by $c_{jk} = (1 - \theta_{jk})b_{jk}$, where c_{jk} and θ_{jk} represent actual household consumption and the waste rate for product category j in region k, respectively. Just like the ω's, the θ's are bounded between zero and one.

The waste rates are assumed to be exogenous (de Gorter et al., 2021). We obtain estimates of the waste rate baseline values from the literature and calibrate the model accordingly. We then calculate how activity levels in various parts of the economy would be affected if the waste rates could be reduced. The construction of the alternative waste scenarios is based on a review of the ongoing policy debate on food waste prevention, as described in Section 2.4. It is noteworthy that, since our analysis focuses primarily on the industries and consumer product categories that comprise the FSC, the waste rates associated with all non-food industries and product categories are set to zero across scenarios, i.e. the economic model simulates the exogenous shocks on the waste rates of only the food related sectors on the rest of the economy.

We use the superscript 0 to denote the value of the relevant variable in the baseline. Conversely, a variable's value in a generic s-th scenario is identified by the superscript s. The symbol Δ is used to indicate (absolute) change relative to the baseline level. Thus, for example, in response to the waste rate changes implied by scenario s, the output of industry i in country k varies by $\Delta q^s_{ik} = q^s_{ik} - q^0_{ik}$.

If – in spite of the waste rate shock – firms and households continued to use the same quantities of all commodities, the new output levels would be given by $v^s_{ik} = u^0_{ik}/(1 - \omega^s_{ik})$ for all i's and k's. In proportional terms, industry output would change by $(\omega^s_{ik} - \omega^0_{ik})/(1 - \omega^s_{ik})$. In our model, however, a waste rate shock sets off a series of price adjustments, which in turn leads economic agents (both firms and households) to modify their behaviour (e.g. production and consumption levels), then, in general $q^s_{ik} \neq v^s_{ik}$. With a view to analysing the rebound effects of food waste reduction policies, it is useful to break down the output changes associated with scenario *s* into two components:

$$\Delta q^s_{ik} = (v^s_{ik} - q^0_{ik}) + (q^s_{ik} - v^S_{ik}) \tag{1}$$

The first term on the right-hand side can be thought of as a direct effect of the food waste shock. The second term, on the other hand, embodies the response by economic agents. Finally, adjustments to the equations on which Fidelio is based can be found in section A1 of Appendix A.

2.2. Environmental impacts

Following standard practice in input–output analyses (Miller and Blair, 2009), environmental impacts are calculated from the Δq's assuming that they are directly proportional to the level of economic activity. To this end, let e_{ikn} represent emissions of a generic pollutant *n* (or extraction of generic resource *n*) by industry *i* in country *k*. Then, the effect of the *s*-th shock is given by:

$$\Delta e^s_{ikn} = g_{ikn} {}^* \Delta q^s_{ik} \tag{2}$$

where g_{ikn} is a coefficient reflecting environmental impact per unit of output for the relevant combination of industry, country and impact category. We construct the *g*'s from the Exiobase database and keep them fixed across scenarios. As for changes in output levels, environmental impacts can also be thought of as the sum of two terms:

$$\Delta e^s_{ikn} = d^s_{ikn} + r^s_{ikn} \tag{3}$$

where $d^s_{ikn} = g_{ikn} * (v^s_{ik} - q^0_{ik})$ is directly related to the changing waste rate (direct effect), and $r^s_{ikn} = g_{ikn} * (q^s_{ik} - v^s_{ik})$ capturing the economy's response (rebound effect).

As the geographical focus of the analysis is on the EU, waste rates are only shocked in EU countries and our main results are aggregated at the EU level. Thus, the impact of changing industry *i* activity levels on the *n*-th environmental stressor in scenario *s* is given by $\Delta E^s_{in} = \Sigma_{k \in EU} \Delta e^s_{ikn}$. For the purpose of this analysis, we define the EU as consisting of all pre-Brexit Member States. Further, adding up over the industry dimension (*i* subscript) yields an economy-wide measure of impact. The decomposition of environmental impacts into direct and rebound effects carries over naturally to these aggregated results. Emissions and resource extraction directly associated with household consumption activities are not taken into account in our environmental assessment, as they were insensitive to the policy shocks considered.

To convert the emissions to/resources extracted from the environment, i.e. the elementary flows (Δe^s_{ikn}), into the emissions contributing to each impact category, it is necessary to multiply the elementary flows by the characterisation factors for each pollutant and resource extracted for different impact categories ($\Delta I^s_{ikn} = \Delta e^s_{ikn} {}^* C$). The characterisation factors (*C*) are based on the Environmental Footprint EF3.0 (Zampori and Pant, 2019) developed by the European Commission and are obtained as described in Beylot et al. (2019), representing the most up-to-date LCIA method for Europe. Potential impacts were quantified for: climate change; acidification; eutrophication, terrestrial; eutrophication, marine; eutrophication, freshwater; land use; water use; human toxicity, cancer effects; human toxicity, non-cancer effects; ecotoxicity, freshwater; particulate matter; photochemical ozone formation; resource use, minerals and metals; and, resource use, fossil. The inclusion of all 14 impact categories allows to better highlight possible trade-offs when comparing the different scenarios.

Finally, by dividing the impacts by the tonnes of avoided food waste, based on the figures provided in the hybrid version of EXIOBASE 3 (Merciai and Schmidt, 2018, 2016) for the *Agriculture (A01)* sector, we expressed the environmental impacts per tonne of avoided food waste. Details about the calculations performed can be found in section A2.2 of Appendix A.

2.3. Adjustment costs

As a starting point, our calculations are carried out under the assumption that food waste reduction can be attained at no cost. We then expand on this first analysis by contemplating alternative scenarios in which waste avoidance is costly (e.g. to reduce food waste at production, investments are required to optimise the technologies used). To this end, we posit that avoiding the creation of one unit of waste in generic industry *i* in country *k* would cost the producer some fixed amount κ_{ik}. Then, the overall cost of reducing the waste rate from its baseline level ω^0_{ik} to a lower level ω_{ik} is given by $\kappa_{ik}(\omega^0_{ik} - \omega_{ik})q_{ik}$. Net of the adjustment cost, the producer's revenue is:

$$\left[p_{ik} - \kappa_{ik}\left(\frac{\omega^0_{ik} - \omega_{ik}}{1 - \omega_{ik}}\right)\right]u_{ik} \tag{4}$$

where p_{ik} represents the price of industry output *i* in country *k*.

It is apparent from Equation (4) that in our formulation adjustment cost operates like a specific tax of amount $\kappa_{ik}[(\omega^0_{ik} - \omega_{ik}) / (1 - \omega_{ik})]$ on available output (although one that does not generate any revenue for the government) and as such we incorporate it in the modelling framework provided by Fidelio. With the baseline and policy waste rates already determined, the tax rate is defined up to κ_{ik}. To operationalize our approach we only need to specify the cost factors. Given that reliable data on adjustment costs are not available, we consider two alternatives to the free adjustment scenario ($\kappa_{ik} = 0$ for all *i* and *k*) that results in the highest revenues (as it can also be observed from Eq. (4)), a moderate-cost (all the κ's set equal to 0.5), and a high-cost scenario (all κ's set to 1). Indeed, each unit of output that is converted from waste to available product can be sold at the market price. In applied equilibrium models such as Fidelio, all prices are initially normalised to one. Thus, the moderate-cost scenario implies that adjustment cost account for half the additional revenue generated by waste reduction. Analogously, the high-cost scenario assumes that additional revenue is entirely absorbed by adjustment costs. Finally, waste avoidance at the household level can be attained free of cost throughout scenarios.

2.4. Description of the scenarios

The definition of food waste adopted in this study follows the one provided in the FUSIONS project: food waste accounts for both edible and inedible parts of food, which is removed from the FSC to be disposed of or recovered (Östergren et al., 2014).

In the study, we consider two overall goals centered on food waste prevention, namely the Sustainable Development Goal #12.3 (United Nations, 2015) and the Resource Efficiency Roadmap (European Commission, 2011). The former clearly states a quantitative prevention goal (i.e. 50 % reduction) for post-processing food waste (wholesale and retail, food services, and households), but not at the level of pre-consumer food waste (primary production, and production and manufacturing). Therefore, a quantitative reduction goal for pre-consumer food waste was based on the targets of the Resource Efficiency Roadmap, aiming at reducing resource inputs in the FSC by 20 % by 2020 (European Commission, 2011). It is noteworthy that no specific prevention measure is assessed in the study, but rather the economic and environmental effects of achieving the current EU/SD goals is quantified.

These targets were considered in six different scenarios which shocks were defined based on the figures provided in Caldeira et al. (2019) who estimated that the EU-27+1 wasted 123 MT of food across the FSC, excluding wholesale and retail, corresponding to 19 % of the total available food (638 Mt). Households wasted the highest amount of food (50 Mt, corresponding to 8 % of the total available food), followed by primary production (32 Mt, corresponding to 5 % of the total available food), processing and manufacturing (31 Mt, corresponding to 5 % of the total available food) and, finally, food services (10 Mt, corresponding to

2 % of the total available food) (Caldeira et al., 2019).

The scenarios considered in the study (Fig. 1) account for different levels of food wasted across the FSC and resulted in: i) scenario 0: baseline, or business-as-usual, with no prevention policies implemented throughout the FSC (i.e. a "do-nothing" scenario with food waste levels equal to 2011 – 19 % of the total available food is wasted); ii) scenario I: 20 % food waste reduction in primary production (food waste at primary production becomes 4 % of the total available food – the food wasted is 80 % of the 5 % calculated in the baseline – leading to a total of 18 % of food wasted across the entire food supply chain); iii) scenario II: 20 % food waste reduction in processing and manufacturing (food waste at processing becomes 4 % of the total available food, leading to a total of 18 % of food wasted across the entire food supply chain); iv) scenario III: 50 % food waste reduction in food services (food waste at food services becomes 1 % the total available food, leading to a total of 18 % of food wasted across the entire food supply chain); v) scenario IV: 50 % food waste reduction at households (food waste at households becomes 4 % of the total available food, leading to a total of 15 % of food wasted across the entire food supply chain); and, vi) scenario V: the food waste reductions of scenarios I-V are combined (food waste across all stages becomes 13 % of the total available food). It is noteworthy that wholesale and retail was not considered among the stages of the FSC as in Fidelio this is merely an activity providing a service, i.e. trading goods.

3. Results

The economic and environmental results are discussed in Section 3.1 and 3.2, respectively. The results are presented as the difference (in production for the economic results, and impacts for the environmental results) between scenarios I-V and the baseline. Throughout the results we refer to it only with the name of scenarios I-V, e.g. the difference in environmental impacts between scenario I and the baseline is referred to as "scenario I", etc., unless stated otherwise. Furthermore, the results are presented per sector following the aggregation displayed in section A3.1 of Appendix A. The complete list of economic results is reported in section A4 of Appendix A, while the environmental results are listed in sections A5-A6 of Appendix A.

The results obtained in the environmental assessment represent the total (or joint) effect of food waste prevention and macroeconomic rebound effects. Specifically, the results reported for the *Agriculture (A01)* sector represent the saving/burden incurring from food waste prevention and related direct rebound effects. Therefore, to distinguish the savings related to food waste prevention from the burdens incurring from direct rebound effects in the *Agriculture (A01)* sector, the calculation explained in section A2.2 of Appendix A was performed, while the corresponding results are discussed in Section 3.3.

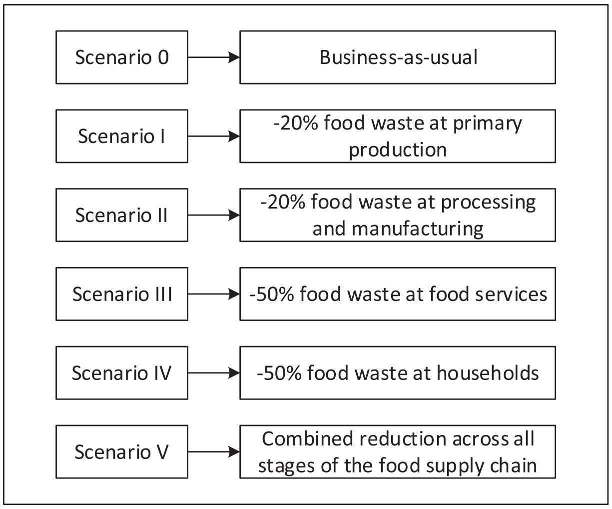

Fig. 1. Summary of the scenarios considered in the assessment.

Finally, in Sections 3.2–3.3, we only discuss impact categories that have robustness factors greater than 0.7, based on the ranking provided in Sala et al. (2018). Therefore, human toxicity, cancer and non-cancer effects, and ecotoxicity freshwater are excluded; yet, their results can be found in sections A5-A6 of Appendix A.

3.1. Results of economic modelling

The scenarios introduced in Section 2.4 shock the EU economy by changing the waste rate at various points in the food supply chain. In each case, the shock sets off a series of adjustments in the economic system that extends beyond food production and consumption. Fig. 2 displays the relative change in output experienced by the various sectors of the economy under the different food waste scenarios.

First, consider what happens to the output of food-related sectors – namely, *Agriculture (A01)*, *Food (C10-C12)*, and *Hotels/Restaurants (I)*. These are the sectors affected most directly by the shocks. Broadly speaking, in these sectors a reduction in the waste rate gives rise to two effects of opposite sign. On one hand, when less output is wasted, the same consumption level can be sustained at a lower level of production. On the other, a reduction in the waste rate effectively makes agricultural and food products cheaper for consumers and processors to use (i.e. suppose that a product can be bought at price p and is wasted at rate ω; then, the price effectively paid for using a unit of the product is $\tilde{p} = p/(1-\omega)$ where a reduction in ω makes the effective price $\tilde{p}$ smaller). The resulting increase in demand (direct rebound effect) tends to lift consumption and output as well. This rebound effect is more pronounced when waste reduction is free ($\kappa = 0$, Fig. 2a). When waste reduction is moderately ($\kappa = 0.5$, Fig. 2b) or highly expensive ($\kappa = 1$, Fig. 2c), the price-reducing effect of the waste shock is at least partly offset by the adjustment cost.

In scenario I, for instance, in the absence of adjustment costs the rebound effect dominates: overall output of food-related sectors is calculated to increase by 1.2 %, with more than two-thirds of the change accounted for by *Agriculture (A01)*, the sector where the shock takes place in this scenario. Once reducing food waste becomes costly, however, agricultural production actually experiences a decrease – by 0.94 % with $\kappa = 0.5$, and by 1.74 % with $\kappa = 1$. The introduction of the adjustment costs also has repercussions on the output of the *Food (C10-C12)* (+0.01 % with $\kappa = 0.5$ and −0.10 % with $\kappa = 1$) and *Hotels/restaurants (I) sectors* (+0.01 % with $\kappa = 0.5$ and −0.05 % with $\kappa = 1$).

The results for scenario II are qualitatively similar to those obtained for scenario I. In the *Food (C10-C12)* sector, the impact of the waste shock on production ranges from + 3 % ($\kappa = 0$) to −1.8 % ($\kappa = 1$). Concerning the other food-related sectors, the relative change in output is between 0.06 % (with $\kappa = 0$) and −0.6 % ($\kappa = 1$) for *Agriculture (A01)*, and between 0.4 % ($\kappa = 0$) and −0.2 % ($\kappa = 1$) for *Hotels/restaurants (I)*.

In the case of scenario III, on the other hand, output decreases already in the absence of adjustment costs: *Agriculture (A01)* decreases its output from −0.02 % ($\kappa = 0$) to −0.05 % ($\kappa = 1$), *Food (C10-C12)* from −0.04 % ($\kappa = 0$) to −0.06 % ($\kappa = 1$), and, finally, *Hotels/restaurants (I)* from −0.2 % ($\kappa = 0$) to −0.9 % ($\kappa = 1$).

Contrary to scenarios I-III, which all consider waste reductions on the supply-side of the economy, scenario IV focuses on consumers. As noted above (Section 2.3), in this case it is assumed that households do not face any adjustment costs, so that the results in Fig. 2 are constant across panels a, b and c. The results for scenario IV suggest that initiatives applied at this stage have the greatest potential for reducing output (Fig. 2). Indeed, production would drop by −2.5 % for *Agriculture (A01)* and by −3% for *Food (C10-C12)*, representing the largest reductions among scenarios I-IV.

Finally, scenario V combines all the prevention initiatives considered in scenarios I-IV. The economic output of food-related activities decrease whether or not adjustment costs are accounted for, with the

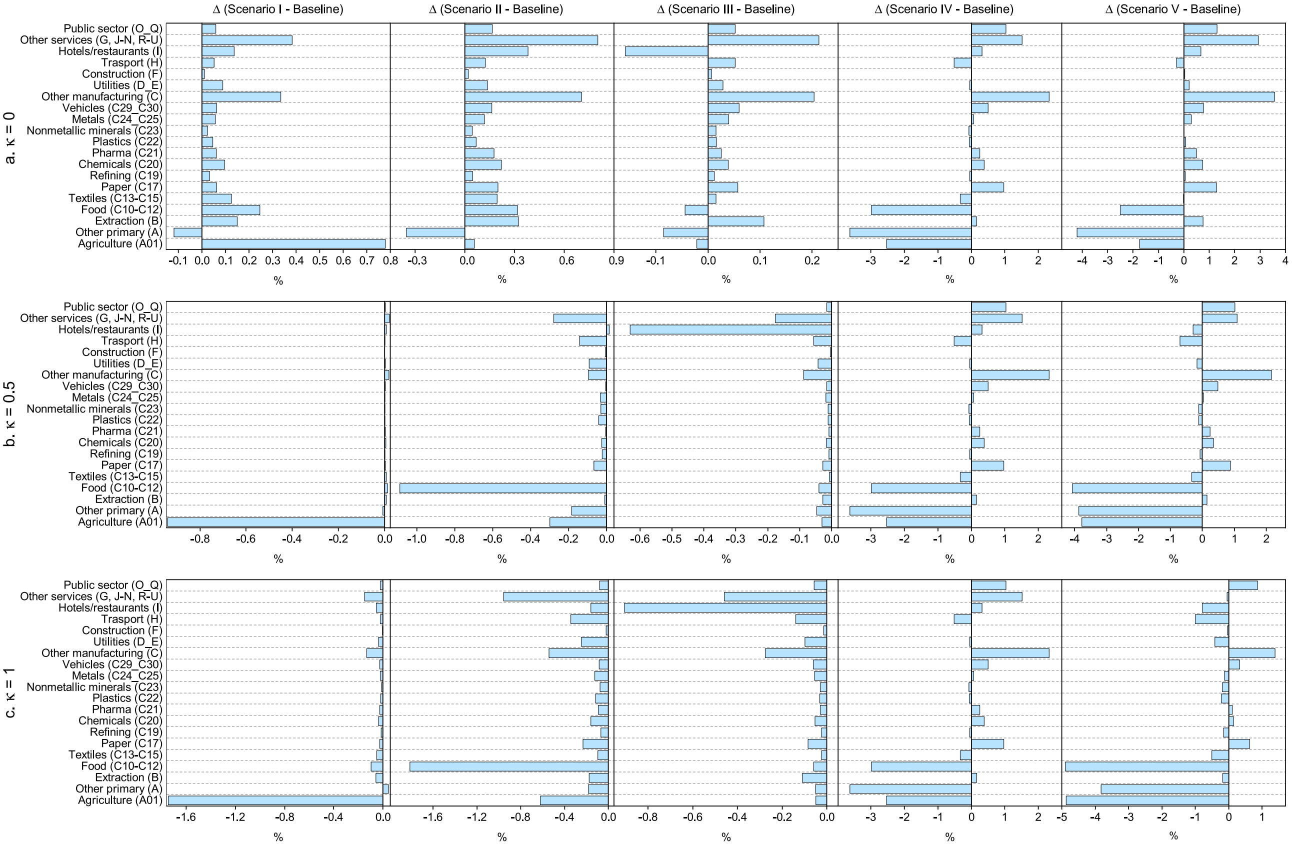

Fig. 2. Variation in the economic output expressed as percentage changes [%] between scenarios I-V and the baseline. Negative values indicate a reduction in the economic output in scenarios I-V compared to the baseline, while the vice versa applies for positive values. The results presented in 2a refer to the set of scenarios where there are no adjustment costs (i.e. κ = 0), the ones presented in 2b to adjustment costs accounting for half the additional revenue generated by waste reduction (κ = 0.5), while the ones presented in 2c to adjustment costs entirely absorbing the revenue (κ = 1). Note that the NACE2 nomenclature is reported in parenthesis on the y-axis.

reduction becoming more sizable as the adjustment costs increase: *Agriculture (A01)* drops from −1.8 % (κ = 0) to −4.9 % (κ = 1), *Food (C10-C12)* from −2.5 % (κ = 0) to −4.9 % (κ = 1), *Hotels/restaurants (I)* from 0.7 % (κ = 0) to −0.8 % (κ = 1).

Leaving food-related sectors aside, how is the rest of the EU economy affected by the food waste shocks? Throughout scenarios I-III, when the adjustment costs are zero reducing waste in the food supply chain has an expansionary effect on the economy, raising production in all non-food sectors. As adjustment costs increase, however, this effect gradually disappears or reverses. In scenario IV, the (cost-free) reduction in household-level food waste frees up resources that consumers reallocate to a significant extent to non-food expenditure. This also tends to increase production. In scenario V, which blends together scenarios I-IV, the most significant impacts on the output of non-food sectors are found in *Other manufacturing (C)* (from 3.6 % at κ = 0, to 1.4 % at κ = 1), *Other services (G, J-N, R-T)* (from 2.9 % at κ = 0, to −0.05 % at κ = 1), *Public sector (O_P)* (from 1.3 % at κ = 0, to 0.9 % at κ = 1), and *Paper (C17)* (from 1.3 % at κ = 0, to 0.6 % at κ = 1).

3.2. *Environmental results*

In all three sets of scenarios, for the majority of impact categories considered in the study, the results highlighted that food waste prevention initiatives applied at consumption stages reduced total impacts. When prevention policies were applied at production stages, namely scenarios I-II, and under the assumption of no adjustment costs, the burdens from direct and indirect rebound effects cancelled out the benefits of avoiding food waste (i.e. backfire effect), thus resulting in higher impacts compared to the baseline. Yet, when assuming adjustment costs different from zero, lower environmental impacts than the baseline were observed also for the abovementioned scenarios. Furthermore, the results highlighted that as adjustment costs increased, the environmental burdens of the FSC decreased due to reductions in food production and the associated waste generation (section A5, Appendix A).

3.2.1. *Climate change*

The results obtained for climate change are displayed in Fig. 3, where negative values indicate savings in scenarios I-V, while the vice versa applies for positive values.

Under the assumption of κ = 0, an increase of 6.5 Mt CO_2-eq year^{-1} in scenario I, 3.5 Mt CO_2-eq year^{-1} in scenario II, and 0.6 Mt CO_2-eq year^{-1} in scenario III, was observed in the total Climate Change burdens due to increases in the economic output (i.e. backfire effect) (Section 3.1). In scenarios IV-V the total burdens decreased by 16.4 Mt CO_2-eq year^{-1} and 6.1 Mt CO_2-eq year^{-1}, respectively. Notice that the total potential savings obtainable at food related sectors were reduced by increases in the other economic sectors (rebounds). However, as adjustment costs increased (κ = 0.5 and κ = 1), a reduction in the burden was observed also for scenarios I-III due to decreases in the economic output (Section 3.1). In scenarios I-V, increasing adjustment costs reduced the burdens of both food related sectors and the other sectors, especially for *Utilities (D_E)* and *Extraction (B)* (Fig. 3).

3.2.2. *Eutrophication, acidification, particulate matter and photochemical ozone formation*

The impact categories eutrophication (marine, freshwater and terrestrial), acidification and particulate matter showed similar trends

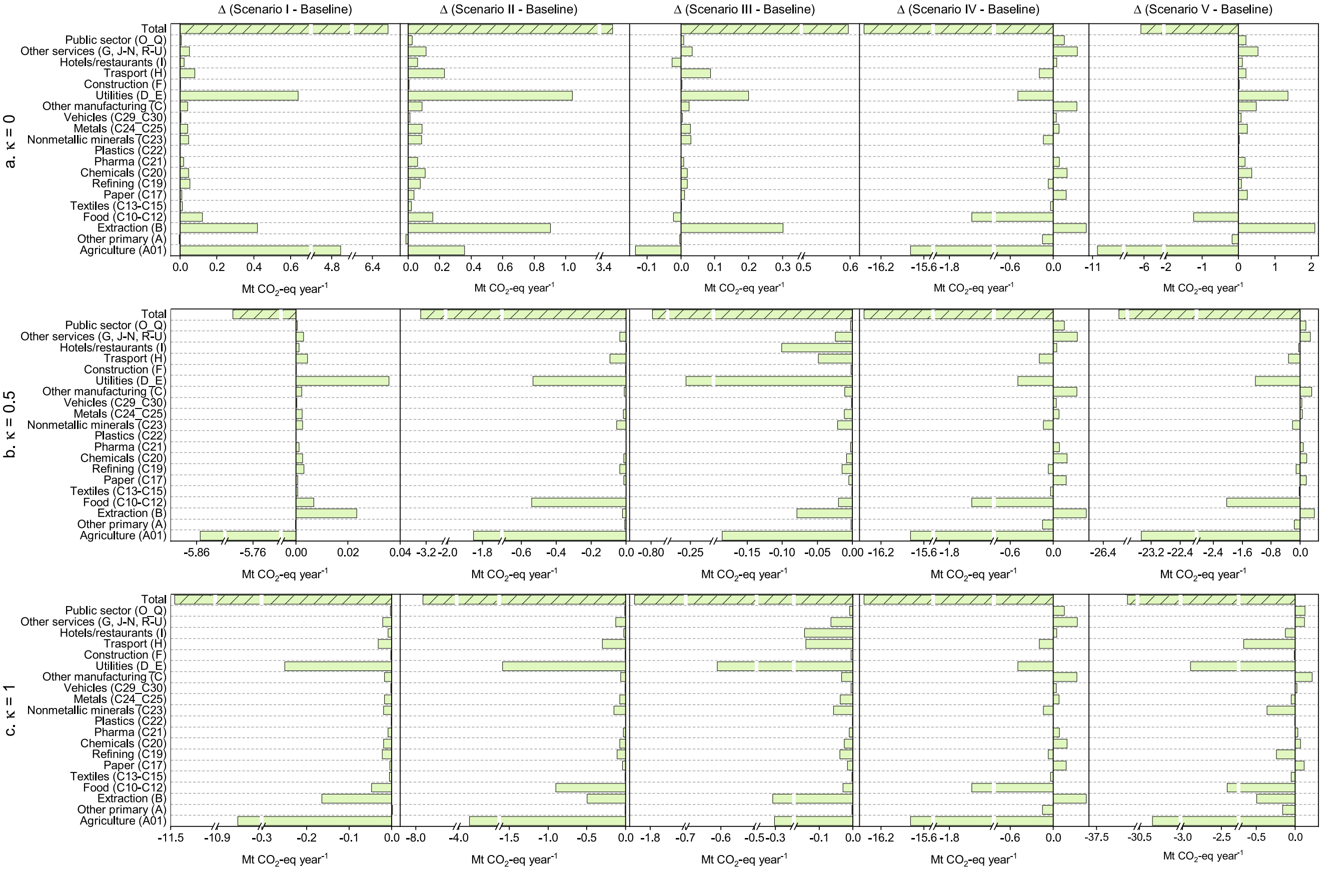

Fig. 3. Difference in emissions [Mt CO$_2$-eq year^{-1}] between scenario I-V and the baseline for the climate change. Negative values indicate savings in scenarios I-V compared to the baseline, while the vice versa applies to positive values. The results presented in 3a refer to the set of scenarios where there are no adjustment costs (i.e. κ = 0), the ones presented in 3b refer to adjustment costs accounting for half the additional revenue generated by waste reduction (κ = 0.5), while the ones presented in 3c refer to adjustment costs entirely absorbing the revenue (κ = 1). Note that the NACE2 nomenclature is reported in parenthesis on the y-axis.

(Appendix A5). As adjustment costs increased, the total burdens calculated for scenarios I-V decreased, i.e. a reduction in emissions compared to the baseline was observed. Specifically, for κ = 0, backfire effects were observed for scenarios I-II, while in scenarios III-V the reduced emissions in food sectors counterbalanced the increased burdens, which were mainly related to *Utilities (D_E)* and *Transport (H)* for eutrophication and acidification, and *Utilities (D_E)*, *Transport (H)* and *Extraction (B)* for particulate matter. When adjustment costs were assumed different from zero, scenarios I-V all incurred lower total burdens than the baseline, with the highest reductions at κ = 1. Furthermore, the results showed that for all sets of scenarios, scenario IV had the greatest potential in reducing impacts.

The results obtained for photochemical ozone formation followed the same trend as for eutrophication, acidification and particulate matter at κ = 0.5 and κ = 1. Yet, at κ = 0, scenarios I-III and scenario V resulted in backfire effects, which were mainly related to the sectors *Utilities (D)*, *Transport (H)*, *Other services (G, J-N, R-U)*, and *Extraction (B)* (Appendix A5).

3.2.3. Land use and water use

The results obtained for land and water use followed the trend observed for the eutrophication related impact categories (Section 3.2.2). When adjustment costs were assumed to be zero, scenarios I-II resulted in backfire effects (Appendix A5), while scenarios III-V incurred lower burdens than the baseline due to the benefits of decreased production and wastage of food. At κ = 0.5 and κ = 1, the burdens of scenarios I-II also decreased compared with the baseline, thus increasing the potential reductions observed in scenario V, which comprehends all shocks. As for the non-food related sectors, in the impact category land use *Other primary (A)* was mainly affected due to forestry and logging (sector *A02*), while for water use *Paper (C17)*, *Chemicals (C20)*, *Utilities (D_E)*, and *Other services (G, J-N, R-T)*.

3.2.4. Resource use, fossil and resource use, minerals and metals

The results obtained for resource use, fossil and resource use, minerals and metals showed a different trend than the other impact categories. For both impact categories, at κ = 0 scenarios I-V all incurred in backfire effects due to increases in the economic output for *Extraction (B)*. At κ = 0.5, the results obtained for scenarios I, IV, and V resulted in higher burdens than the baseline, while at κ = 1 all scenarios, except for scenario IV, incurred lower burdens than the baseline.

3.3. Results expressed per tonne of avoided food waste

The results calculated as the difference between scenarios I-V and the baseline at κ = 0.5 expressed per tonne of avoided food waste are presented in Fig. 4. The results display the contribution analysis to the total impacts of direct rebound effects and food waste prevention in the *Agriculture (A01)* sector, other food related sectors (as the sum of related direct rebound and prevention effects), indirect rebound effects, and the totals obtained for κ = 0 (blue dot in Fig. 4) and κ = 1 (red square in Fig. 4). It is noteworthy that direct and indirect rebound effects take into account economy-wide effects as well thus representing macroeconomic rebound effects.

As illustrated in Fig. 4, the impact of food waste prevention (per impact category) is constant across scenarios and is calculated based on the results obtained for the baseline on the assumption that the impacts for producing food would be unchanged. By disaggregating the

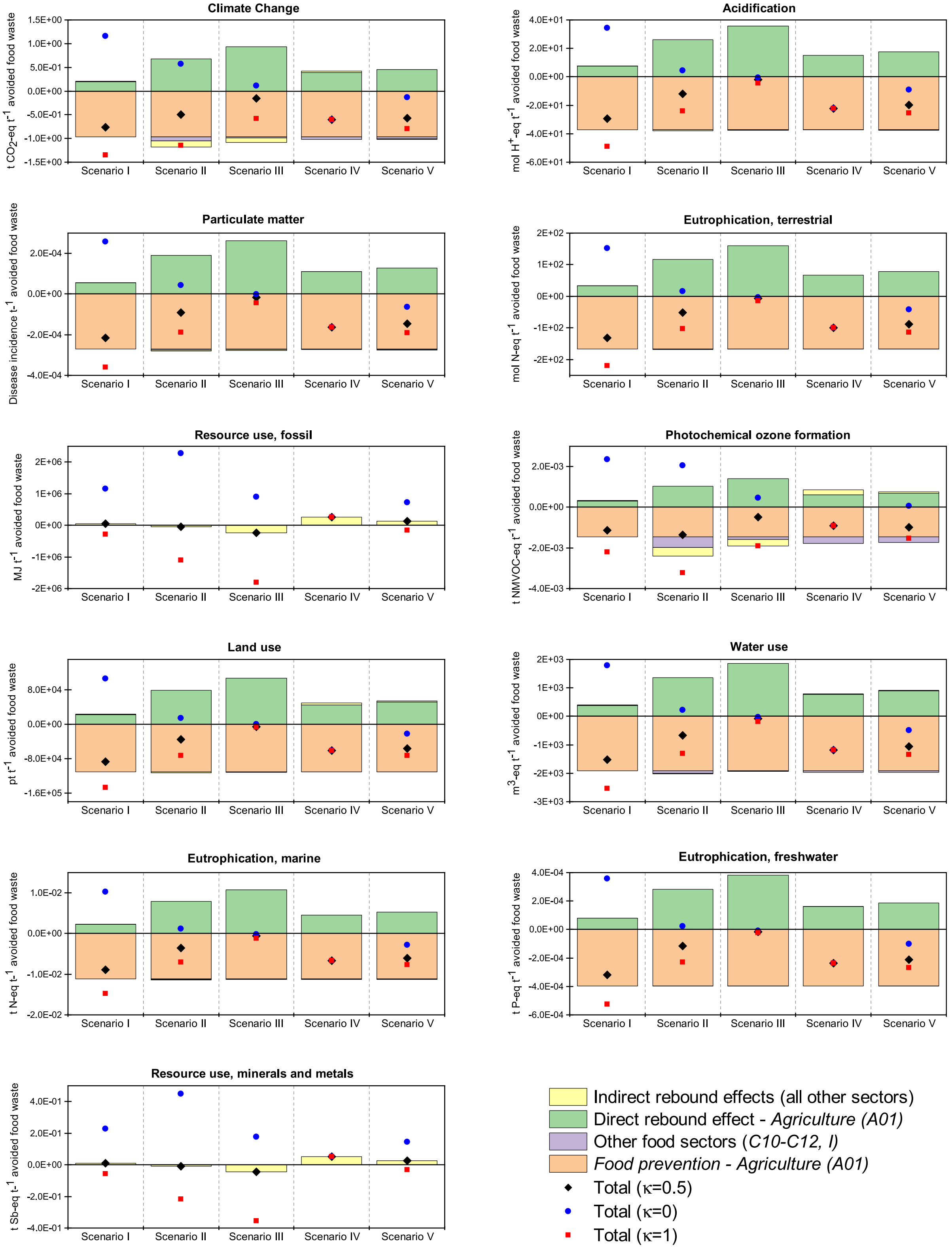

Fig. 4. Environmental results for κ = 0.5 expressed per tonne of avoided food waste. The histograms report the contribution to the total results (i.e. black diamond) of direct rebound effects and food waste prevention in the *Agriculture (A01)* sector, other food sectors, and indirect rebound effects. Negative values indicate a reduction in the burdens of scenarios I-V compared with the baseline, while the vice versa applies for positive values. The total results obtained for κ = 0 (blue circle) and κ = 1 (red square) are also reported for comparison. The rebound effects herein reported are macroeconomic rebound effects, which, therefore, take into account economy-wide effects.

contribution of rebound effects (inclusive of direct, indirect, and economy-wide effects), it was possible to calculate the reduction of the benefits associated with prevention (avoiding food waste generation) for each impact category and scenario considered in the study. All in all, the results in the majority of impact categories are driven by food waste prevention and direct rebound effects on the *Agriculture (A01)* sector. Only for resource use, fossil and resource use, metals and minerals the results were driven entirely by indirect rebound effects and, specifically, the *Extraction (B)* sector. As follows, we present only the results obtained for $\kappa = 0.5$ and scenario IV, while the complete list of the results can be found in section A6 of Appendix A.

For climate change, the savings related to prevention equalled approximately 1 t CO_2-eq t^{-1} avoided food waste, which was reduced by 38 % due to macroeconomic rebound effects. For the impact categories acidification, particulate matter, and eutrophication, marine, the potential benefits of food waste prevention were reduced by 40 %, while for eutrophication, freshwater and terrestrial by 41 %. Food waste prevention savings were reduced for land use and water use by 45 % and 38 %, respectively. Finally, for resource use, fossil and resource use, minerals and metals, the results indicated backfire effects.

4. Discussion

4.1. Differences in economic and environmental impacts

The economic results showed that food waste prevention initiatives at production stages have the potential to increase agricultural and food production, at least when they do not entail any adjustment costs for producers. This is because a waste reduction effectively represents an improvement in productivity. Accordingly, it tends to expand economic activity. Instead, when prevention was enforced at the consumption stages, a decrease in food production was observed. However, as adjustment costs increase, a decrease in productivity in all food related sectors was observed, which influenced also the non-food sectors causing a reduction in their economic output. The same trend was observed in the environmental results: overall, a reduction in the environmental burdens was observed as adjustment costs increased. Furthermore, the environmental results also showed that the greatest potential in reducing impacts could be achieved implementing prevention initiatives at post-processing stages, especially at households.

Focusing on the indirect rebound effects, the sectors mainly contributing to the results differed in the economic and in the environmental assessments. From the economic results, *Other manufacturing (C)*, *Other services (G, J-O, R-T)*, and to a lower extent *Extraction (B)*, *Public sector (O—P)*, and *Paper (C17)* mainly experienced increases in the economic output. With respect to the environmental results, *Extraction (B)*, *Utilities (D_E)*, *Transport (H)*, *Chemicals (C20)* and, to a lower extent, *Other manufacturing (C)* and *Other services (G, J-O, R-T)* were identified as the main contributors to indirect rebound effects. The discrepancies between the economic and the environmental results showed that, despite having small increases in the economic output, sectors that are mainly fossil based and/or require many resources (e.g. *Extraction (B)* and *Utilities (D_E)*) have high impacts on the environment and can potentially cancel out the environmental savings from prevention actions, especially under the assumption of no adjustment costs incurred by food industries.

4.2. Comparison with previous studies

As the majority of the published studies focused on food waste prevention at households estimating solely climate change impacts, it was possible to compare the results obtained for scenario IV and climate change only, leading to potential burden shifts across the other impact categories.

The results obtained in scenario IV for climate change, under the assumption of no adjustment costs, for the *Agriculture (A01)* sector (-15.8 Mt CO_2-eq $year^{-1}$) were in line with the findings of Philippidis et al. (2019) and Höjgård et al. (2013), who estimated in their assessment a reduction in climate change impacts of 16 Mt CO_2-eq. In their study, Philippidis et al. (2019) accounted for direct rebound effects only, which were estimated using MAGNET, a computable general equilibrium model focused on the agri-food sector. MAGNET allows identifying in the *Agriculture (A01)* sector for what products there is a reduction, while this level of detail cannot be obtained with Fidelio, having as ultimate goal to model market responses in the entire economy. The results of Höjgård et al. (2013) were obtained employing the partial equilibrium model CAPRI, which is specific for agricultural assessments. However, being CAPRI a partial equilibrium model, the effects of indirect rebound effects are not quantified.

As for the results expressed per tonne of avoided food waste, in the study by Martinez-Sanchez et al. (2016) rebound effects ranged from 1.5 t to 4.4 t CO_2-eq t^{-1} avoided food waste, which are higher than those estimated in this study (0.4 t CO_2-eq t^{-1} avoided food waste). As highlighted in Salemdeeb et al. (2017), in the study by Martinez-Sanchez et al. (2016) a highly aggregated economic model was used to estimate the re-spending of households. Furthermore, the assumptions made on the goods that were affected by prevention initiatives were chosen based on extreme scenarios rather than elasticity-based simulations, as in the current study. The estimated rebound effects calculated herein were of the same order of magnitude of Salemdeeb et al. (2017). In their study, under the assumption that consumers purchase the most consumed goods, rebound effects spanned from 0.3 to 0.33 t CO_2-eq t^{-1} avoided food waste. On the other hand, when the authors assumed the purchasing of goods with the highest GHG intensities, rebound effects spanned from 0.6 to 0.8 t CO_2-eq t^{-1} avoided food waste. Of the total rebound effects estimated in Salemdeeb et al. (2017), approx. 0.3 t CO_2-eq t^{-1} avoided food waste was attributable to direct effects when assuming that consumer purchase the most polluting goods and 0.1 when assuming purchasing the most consumed goods, which are in the same order of magnitude of the direct rebound effects estimated herein (approx. 0.4 t CO_2-eq t^{-1} avoided food waste). Differences in the magnitude of direct and indirect rebound effects between our study and Salemdeeb et al. (2017) are due to the type of analysis conducted. In our study, macroeconomic rebound effects were quantified, while in Salemdeeb et al. (2017) microeconomic effects only were quantified. It should however be noticed that, all in all, the reduction in the benefits of prevention calculated in our study (38 %) was comparable to Salemdeeb et al. (2017) (ranging from 23 to 59 %). However, Salemdeeb et al. (2017) did not consider any adjustment costs, the inclusion of which highly affects the results as shown in our study.

4.3. Policy implications

The results obtained showed that reductions in environmental impacts can be achieved when implementing prevention actions across the entire FSC. Of all stages, both from an economic and an environmental perspective, food prevention initiatives are most effective at households, which have been identified in previous studies as the main food waste generators and polluters (Tonini et al., 2018), notwithstanding possible rebound effects. This suggests that policies targeting the households have the largest potential to mitigate the pressure on food related sectors. However, in order to maximise the benefits, the policy needs to support a “sustainable” re-spending of the income. Indeed, despite being moderate from an economic perspective, it was observed that the increased consumption in *Extraction (B)*, *Transport (H)*, and *Other utilities (D_E)* significantly reduced the benefits achieved with preventing food wastage because of their considerable impact on the environment. Therefore, it is crucial to install incentives to direct consumption expenditures towards sectors that have low/negligible environmental impacts but also have positive societal outcomes, such as health, education and culture.

5. Conclusion

While it is largely acknowledged and documented that food waste prevention is the preferred option in the waste management hierarchy, rebound effects arising from prevention are usually not accounted for in life cycle assessment studies. Rebound effects arise due to accrued additional monetary savings that can be spent on the same products (direct) or other products/services (indirect). In this study, the market response of implementing prevention initiatives was assessed by means of Fidelio, a general equilibrium model that allows calculating macroeconomic rebound effects based on price elasticities and cross-elasticities. The economic results were further converted into environmental impacts by performing an environmentally extended input–output assessment in which fourteen impact categories were included. The economic and environmental results showed that initiatives implemented at households have the greatest potential in reducing total burdens (-5.2 % from the economic perspective; for climate change a reduction of 16.4 Mt CO_2-eq year^{-1} compared with the business-as-usual). The results also pinpointed that such initiatives to be effective need to promote the spending on economic sectors characterised by low environmental impacts and resource consumption, such as the public sector, and that the inclusion of adjustment costs in the analysis is crucial to obtain realistic results.

6. Disclaimer

The views expressed in the article are the sole responsibility of the authors and in no way represent the views of the European Commission and its services.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

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