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The climate impact of excess food intake - An avoidable environmental burden

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ABSTRACT

The environmental impacts of food systems and the health consequences of excess food intake are well-acknowledged global issues. However, the climate impact of excess food intake, or metabolic food waste, has received less attention. This study estimated the amount of metabolic food waste and its climate impact in Sweden. Excess food intake was estimated based on the adult overweight and obesity prevalence in Sweden, by applying two alternative calculation methods, one based on the energy content of excess body fat, and the other based on the excess energy intake due to excess body fat. These caloric values were translated to food consumption patterns according to three dietary scenarios and their climate impact estimated based on carbon footprint data. The results showed that the annual amount of metabolic food waste represented 480–710 kt of food in Sweden and, regardless of dietary scenario, exceeded the annual amount of avoidable household food waste. The estimated greenhouse gas emissions from the metabolic food waste amounted up to 1.2 Mt CO_2e annually, accounting for approximately 2% of the total and 10% of the food-related climate impact in Sweden. This study confirms the magnitude of the hidden climate cost of excess food intake on a national level and emphasizes the importance of taking this aspect into consideration in actions to improve both planetary and human health. Although applied to the Swedish context, the methodology used in the present study could also be used to assess the environmental impact of excess food intake in other countries globally.

1. Introduction

Modern food systems are largely unsustainable, posing a threat to global food security, partly because of the high environmental impact of food production and consumption. The agricultural sector is in fact a major user of finite natural resources such as freshwater and land, contributing e.g., to soil degradation, deforestation, and loss of biodiversity (FAO, 2018). Moreover, industrialized food systems account for 19–29% of the total global anthropogenic greenhouse gas emissions (GHGEs), making them a major contributor to climate change, the defining challenge of our time (Vermeulen et al., 2012).

Another aspect of the unsustainability of food systems is food loss and food waste generated throughout the supply chain from agricultural production to household consumption. Approximately one-third of the food produced globally for human consumption is either lost or goes to waste, accounting for up to 5.9 Gt carbon dioxide equivalents (CO_2e) in annual GHGEs (Gustavsson et al., 2011; Porter and Reay, 2016). The costs of global food wastage are considerable. While the global food and grocery retail market was valued at US$11.7 trillion in 2019, the costs related to global food wastage were estimated to reach US$2.6 trillion annually with economic, environmental, and social costs included (FAO, 2014; GVR, 2020a). Further, the food waste management market was valued at US$30 billion with a projected annual growth rate of 5.4% until 2027 (GVR, 2020b). While food waste treatment facilities are a necessity, investments in such infrastructure could also entail lock-in effects leading to an unwillingness to reduce food waste (European

Abbreviations: BMI, body mass index; MFW_{EEI}, metabolic food waste corresponding to excess energy intake; MFW_{EBF}, metabolic food waste corresponding to excess body fat; NW, normal weight; OB, obese or obesity; OW, overweight.

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Parliament, 2017).

In low-income countries, food is typically lost in the early and middle stages of the food supply chain, while in middle- and high-income countries most food waste occurs once food reaches the consumer (Gustavsson et al., 2011). Sweden is no exception, with high losses reported from retail, food services and households (Brancoli et al., 2019; Eriksson et al., 2020; 2017; 2014; Malefors et al., 2019; Swedish Environmental Protection Agency, 2020). In 2018, more than 0.9 Mt of the 1.3 Mt of food waste generated in Sweden came from households according to the Swedish Environmental Protection Agency (2020). In this case, food waste generated throughout the food value chain from primary production to households was included, and the household food waste contained both food waste, and food and drinks discarded in the drain. Further, 430 kt was considered avoidable, such as food scraps and shriveled or moldy fruit and vegetables, accounting for approximately 920 kt CO_2e in annual GHGEs (Swedish Food Agency, 2016).

Even in countries like Sweden with advanced waste management systems emphasizing resource recovery, only a small fraction of resources invested in food production can be recovered from food waste (Brancoli et al., 2020; Eriksson et al., 2015; Eriksson and Spångberg, 2017). Due to the extent of the unnecessary waste of resources, the food waste issue has become increasingly part of the public agenda. As a global example, target 12.3 for reduction of global food loss and waste is included in The 2030 Agenda for Sustainable Development by the United Nations (UN, 2015). Furthermore, food waste has become a priority for action at both European Union and national levels, including Sweden (European Commission, 2016; Swedish Food Agency et al., 2018).

Modern food systems also contribute to various diet-related diseases, which is another aspect of their unsustainability. Food systems are failing to supply optimal nutrition to everyone, resulting in widespread malnutrition throughout the globe, in wealthy and poor nations alike (WHO, 2020a). Although global food production is sufficient to meet the energy requirements of the global population, 820 million people are still undernourished due to lack of access to food, while nearly 2 billion people have overweight (OW) or obesity (OB) (FAO et al., 2020; WHO, 2020b). OB has become one of the major global health challenges of our time with an estimated cost of US$2 trillion annually (Dobbs et al., 2014; Lehnert et al., 2013). In fact, during the last four decades, the worldwide prevalence of obesity has nearly tripled and is continuing to rise (WHO, 2020a). Moreover, the prevalence of OW and OB among children aged 5–19 has undergone a dramatic rise from just 4 to over 18% during the same time period (Di Cesare et al., 2019). OW and OB, once considered an issue of high-income countries only, is now on the rise in low- and middle-income countries as well affecting every region of the world (WHO, 2020a). Even in high-income countries like Sweden, undernourishment can still be a problem due to food poverty (Bergström et al., 2020), while malnutrition usually comes in the form of overnutrition and poor nutrient balance, leading to high rates of OW and OB. In particular, high consumption of junk foods that are high in sugar, salt, and fat is an established risk factor not only for OW and OB but also for diet-related non-communicable diseases, such as cardiovascular disease (WHO, 2018a, 2020b). In Sweden, 51% of the adult population have now OW or OB and non-communicable diseases are responsible for 90% of all deaths, representing an enormous socioeconomic cost to society (Public Health Agency of Sweden, 2020a; WHO, 2018b; European Commission, 2020).

Excess food intake is considered the fundamental cause of OW and OB (WHO, 2020b). Excess food intake occurs when energy intake exceeds the body's physiological needs, leading to a positive imbalance between energy intake and energy expenditure. The negative health consequences of excess food intake are well acknowledged as a global issue, but the environmental implications of excess food intake have been less well studied. In one study, excess food intake in the American population was estimated as average excess energy intake of 400 kcal/person/day, suggesting an increase in associated environmental impacts due to increased land use, soil loss, energy expenditure, and pollution (Blair and Sobal, 2006). Another study suggested that OB is responsible for higher GHGEs through increased fuel usage, additional food production, and higher amounts of organic waste (Michaelowa and Dransfeld, 2008). Lastly, one study estimated a 19% increase in energy intake required to maintain the basal metabolic rate, corresponding to 300 kt CO_2e per year, by the British population with a hypothetical 40% OB rate (Edwards and Roberts, 2009).

Although excess food intake is seldom included in food system models, studies are emerging where excess food intake is regarded as waste (Porter and Reay, 2016). These studies point to the fact that system losses from excess food intake can be as high as consumer food waste, with similar food security and sustainability implications (Alexander et al., 2017). Others argue that food eaten above physiological needs should be considered waste, and introduce the notion of metabolic food waste as a result of excess body fat accumulated in the population (Serafini and Toti, 2016; Toti et al., 2019).

Estimating the environmental impact of metabolic food waste is a relatively new area of research, and the few studies published so far have also used different methods. To our knowledge, no previous attempt has been made to estimate the amount of metabolic food waste or its climate impact in Sweden. Therefore, the main aim of the present study was to estimate the climate impact of metabolic food waste among the adult population in Sweden, according to three diet scenarios. An additional aim was to apply and compare two methods for quantification of metabolic food waste, based on: a) the energy content of excess body fat, and b) excess energy intake due to excess body fat, in order to find the best-suited method for calculating metabolic food waste.

2. Methods

Excess body fat and excess energy intake were calculated based on the national OW and OB prevalence statistics for the adult population (16 years of age and above) in Sweden (SCB, 2019). The caloric amounts of excess body fat and excess energy intake were converted to metabolic food waste, applying the average results of the latest national adult dietary survey according to three different food intake scenarios (Amcoff et al., 2012). The carbon footprints of metabolic food waste corresponding to excess body fat (MFW_{EBF}) and metabolic food waste corresponding to excess energy intake (MFW_{EEI}) were then derived from the RISE Food Climate Database (version 1.6) (Florén et al., 2017).

2.1. Calculations of excess body fat

Calculations of excess body fat were conducted for each body mass index (BMI) group (normal weight (NW), OW, and OB), for females and males, respectively, prior to averaging them, according to the following steps and based on the assumption that energy balance existed in the whole population:

1) Average body weight was calculated based on average BMI and average height as an inverse function of BMI as:

$$average\ body\ weight\ (kg) = midpoint\ of\ BMI\ cut\ off \times average\ height(m)^2 \quad (1)$$

BMI cut-offs for NW, OW, and OB as defined by WHO (2020b) were used. The midpoints of the cut-offs for the populations with NW (21.8) and OW (27.5) were used as the average BMI for the respective populations. For populations with OB, a statistical average of 33.8 was used, sourced from Statistics Sweden (C Samuelsson, personal communication, 10 Feb 2020).

1) The excess body fat of the population with OW was calculated as the difference in average body weight between the populations with OW and NW as:

$$excess\ body\ fat_{OW} = average\ body\ weight_{OW} - average\ body\ weight_{NW} \quad (2)$$

2) The excess body fat of the population with OB was calculated as the difference between the populations with OB and NW as:

$$excess\ body\ fat_{OB} = average\ body\ weight_{OB} - average\ body\ weight_{NW} \quad (3)$$

3) The excess body fat value obtained, in kg/person, was converted to kcal/person by multiplying by 7778 kcal/kg, corresponding to the energy content of 1 kg body fat (Gibson, 2005).

2.2. Calculation of excess energy intake

Calculations of excess energy intake were conducted for each BMI group and age group, for females and males respectively, prior to averaging them, according to the following steps:

1) Average body weight was calculated based on the average BMI and average height as an inverse function of BMI, using Eq. (1).
2) The average body weight values obtained for females and males, respectively, were inserted into Henry's equation for the respective age groups (Henry, 2005) in order to calculate the average resting energy expenditure. If the age group of the statistical data did not fully match the age groups in Henry's equations, the closest matching alternative was used, e.g., for age group 25–34 Henry's equation for age group 18–29.9 was applied.
3) The resting energy expenditure value was multiplied by the average physical activity level of Swedish adults of 1.6 (Nordic Council of Ministers, 2014), in order to calculate the average total energy expenditure as:

$$total\ energy\ expenditure = resting\ energy\ expenditure \times physical\ activity\ level \quad (4)$$

4) The excess energy intake for the population with OW was calculated as the difference between the average total energy expenditure of the populations with NW and OW as:

$$excess\ energy\ intake_{OW} = total\ energy\ expenditure_{OW} - total\ energy\ expenditure_{NW} \quad (5)$$

5) The excess energy intake for the population with OB was calculated as the difference between the average total energy expenditure of the populations with NW and OB as:

$$excess\ energy\ intake_{OB} = total\ energy\ expenditure_{OB} - total\ energy\ expenditure_{NW} \quad (6)$$

6) The excess energy intake results (kcal/person/day) were multiplied by 365 to convert them to annual amounts.

2.3. Calculation of metabolic food waste

To convert excess body fat (kcal per person) and excess energy intake (kcal per person per year) into foods, i.e., metabolic food waste, the latest national dietary survey, *Riksmaten adults 2010–11*, was used (Amcoff et al., 2012). The aim of the survey was to examine food consumption and nutrient intake among women and men in Sweden. This survey was based on a representative sample of 1797 subjects aged 18–80 years. The participants were asked to report everything they ate and drank during four consecutive days using a validated web-based food record diary (Nybacka et al., 2016a, 2016b). The web-based diary was linked to the food composition database held at the National Food Agency including over 1900 food items and dishes reflecting the local food supply at retail. Composite dishes were divided based on their constituent ingredients, which were distributed to their respective food groups. From the data, average intake of energy and foods was retrieved for men and women, respectively. Foods were retrieved according to the predefined food groups as reported in *Riksmaten*. Data on average percent of energy (E%) for different food groups were not available for men and women separately, but only for the whole population. Based on the data, three different excess food intake scenarios were designed.

In the first scenario, it was assumed that the excess food intake in the population with OW and OB represented excess intake of the average Swedish diet. Thus, the assumption was that the excess food intake followed the average food intake pattern, but in a larger amount. This scenario was therefore named *Swedish average food intake* and consisted of all food groups and items as reported in *Riksmaten* (Table 1).

The second scenario, *Swedish modified food intake*, was intended to represent the food intake of adults with BMI above 25 as reported in *Riksmaten*. However, this diet did not differ significantly from the *Swedish average food intake* scenario, which may be explained by misreporting by this group (Amcoff et al., 2012). Therefore, the modified scenario was further developed by removing fruit, vegetables, coffee, and tea (Table 1). Intake of fruit and vegetables was already below the national recommendation of 500 g/day (Amcoff et al., 2012), so it was considered justified not to consider any part of the fruit and vegetable intake as metabolic food waste. In addition, fruit, vegetables, coffee, and tea were considered not to contribute to OW, due to their low energy content. The excess energy content of the excluded fruits and vegetables was proportionally distributed among the food items that remained in this scenario.

The third scenario, *Swedish junk food intake*, was based on the average intake of sweets, snacks, and soda only, as reported in *Riksmaten* for the general adult population (Table 1).

To calculate metabolic food waste, the average excess caloric amounts, corresponding to excess body fat and excess energy intake, were proportionally distributed among the food items included in the three diet scenarios. As a result, MFW_{EBF} in kg of food, and MFW_{EEI} in kg of food per year, could be calculated.

2.4. Calculation of the climate impact of metabolic food waste

To estimate the climate impact of the excess food intake, metabolic food waste food items were first adjusted for the average food retail and consumption waste percentages (FW%), available from the Food and Agricultural Organization (FAO) (Gustavsson et al., 2011) (Table 1). For a detailed description of how FW% was derived for the foods in the three scenarios, see Table S1 in Supplementary Material. The climate impact of MFW_{EBF} and MFW_{EEI} was derived from the RISE Food Climate Database (Florén et al., 2017), which aims to be representative of Swedish food consumption and reflects the dominant production methods used to produce food for the Swedish market. The database is a collection of carbon footprints from LCA assessments from multiple sources performed both in Sweden and internationally. The database is yearly updated, and the version used in this study includes studies up to October 2019 (RISE, 2019). The database has been recently applied in studies where the nutritional quality of foods and diets has been related to their climate impact (Strid et al., 2021a, 2021b; Mehlig et al., 2020). For more information on the climate data used in this study, see Supplementary Material 2. The climate impact was expressed as kg CO_2e per

Table 1
Dietary scenarios describing food intake patterns associated with excess energy intake.

Swedish average food intake			Swedish modified food intake			Swedish junk food intake		
Food Item	MFW_{EEI} (kg/person/year)	MFW_{EEI} adjusted* (kg/person/year)	Food Item	MFW_{EEI} (kg/person/year)	MFW_{EEI} adjusted* (kg/person/year)	Food Item	MFW_{EEI} (kg/person/year)	MFW_{EEI} adjusted* (kg/person/year)
Fruit and vegetables	24.2	32.8	Potatoes	9.8	12.7	Jam, marmalade	5.6	6.4
Potatoes	9.0	11.7	Cereals	16.7	22.7	Crisps, popcorn	2.0	2.2
Cereals	16.3	22.1	Meat, fish, eggs	15.5	18.2	Nuts, seeds	2.4	2.7
Meat, fish, eggs	14.2	16.8	Dairy	24.6	26.6	Ice cream	4.5	4.9
Dairy	23.6	25.5	Added fats	1.0	1.1	Candy & chocolate	6.1	6.9
Added fats	1.0	1.1	Drinks (incl. alcohol; excl. coffee, tea)	21.0	21.4	Buns, cakes	17.5	23.7
Drinks (incl. alcohol)	58.4	78.0	Sweets, snacks and soda	18.2	20.2	Sweet soups & sauces	5.9	6.7
Sweets, snacks and soda	17.0	18.9	Other	9.8	11.1	Desserts	3.3	4.5
Other	8.9	10.1				Sugar, syrup, honey, sweeteners	1.4	1.6
						Juice, soda, cider	49.3	50.6
						Light: juice, soda, cider	15.4	15.8

* MWF is adjusted for food-specific retail and consumer food waste percentages.

kg food product and included all significant GHGEs from primary production up to industrial processing excluding packaging, and excluding also emissions from land-use change, even though these emissions in certain cases can have a major impact, as illustrated by Eriksson et al. (2018).

The carbon footprint was calculated for the food groups and items following the food categorization as reported in *Riksmaten*. Where food items corresponded to broad food groups (i.e., fish and seafood), their climate impact was derived as consumption-weighted averages of the GHGE from specific foods (i.e., salmon, shrimp, etc.) based on national consumption patterns (Swedish Board of Agriculture, 2018; Ziegler and Bergman, 2017). If consumption statistics were not available for certain food items, the climate impact of the corresponding food group was derived as non-weighted averages. When LCA data were missing, climate data were estimated, modeled, or calculated by RISE personnel (i.e. alcoholic beverages with different alcohol percentages). For more detailed composition and aggregation of the food groups, see Table S2 in Supplementary Material. Further, climate impact data referred to the edible part of foods in the prepared form. As *Riksmaten* does not provide information on whether the foods are cooked or non-cooked, it was assumed that: a) the climate data for vegetables, fruit, and berries were calculated based on non-cooked foodstuffs; b) the climate data for potatoes, rice, pasta, meat, poultry, fish, seafood, and eggs were calculated based on cooked foodstuffs; and c) since there can be different preparation methods for the same foodstuff, the carbon footprint corresponding to the most common cooking methods was used. Lastly, the GHGEs of metabolic food waste were calculated by multiplying the amounts of metabolic food waste by the carbon footprint for each food item.

3. Results

3.1. Excess body fat and excess energy intake in the Swedish adult population

The average excess body fat was 17 and 36 kg per person for the Swedish adult population with OW and OB respectively, corresponding to 135 000 and 279 000 excess kcal per person (Table 2). On a population level, excess body fat amounted to 93 kt in total, corresponding to 727 billion kcal for the Swedish adult population with OW and OB in 2018. Furthermore, the average excess energy intake was 131 000 and 265 000 kcal per person and year for the Swedish adult population with OW and OB, respectively (Table 2). On a population level, excess energy intake amounted to 699 billion kcal per year as a total for the Swedish adult population with OW and OB in 2018.

Table 2
Excess body fat (EBF) and excess energy intake (EEI) of the Swedish adult population with overweight (OW) and obesity (OB) in 2018.

		OW	OB
Gender (M/F)*	million people	1.74 / 1.22	0.6 / 0.57
EBF	kg/person	17	36
EBF	kcal/person	135 000	279 000
EEI	kcal/person/y	131 000	265 000

* Source: Statistics Sweden (SCB), 2019.

3.2. Metabolic food waste

The values of MFW_{EBF} and MFW_{EEI} were similar in magnitude, although it should be noted that their units differ (Fig. 1). Further, the metabolic food waste results varied to some extent depending on the food intake scenario. The *Swedish average food intake* scenario resulted in the largest amounts of both MFW_{EBF} and MFW_{EEI}. In comparison, the results of the *Swedish modified food intake* and *Swedish junk food intake* scenarios were both approximately 33% lower, but similar to each other.

Food groups contributing most to metabolic food waste also varied depending on the food intake scenario. Due to the similarity of the results for MFW_{EBF} and MFW_{EEI}, the food groups are only presented for MFW_{EEI} (Fig. 2). For the *Swedish average food intake* scenario, MFW_{EBF} amounted to 180 kg per person and 743 kt of food as a total for the Swedish adult population. For MFW_{EEI}, the amounts were 173 kg per person and year and 713 kt of food per year in total. The food groups contributing most to MFW_{EEI} were, in descending order: 1) *drinks including alcoholic beverages*; 2) *fruit and vegetables;* and 3) *dairy products* (Fig. 2). For the *Swedish modified food intake* scenario, MFW_{EBF} amounted to 120 kg per person and 497 kt of food in total for the Swedish adult population. MFW_{EEI} was 117 kg per person and year and 481 kt of food per year in total. The food groups contributing most to MFW_{EEI} were, in descending order: 1) *dairy products*; 2) *drinks (including alcohol but*

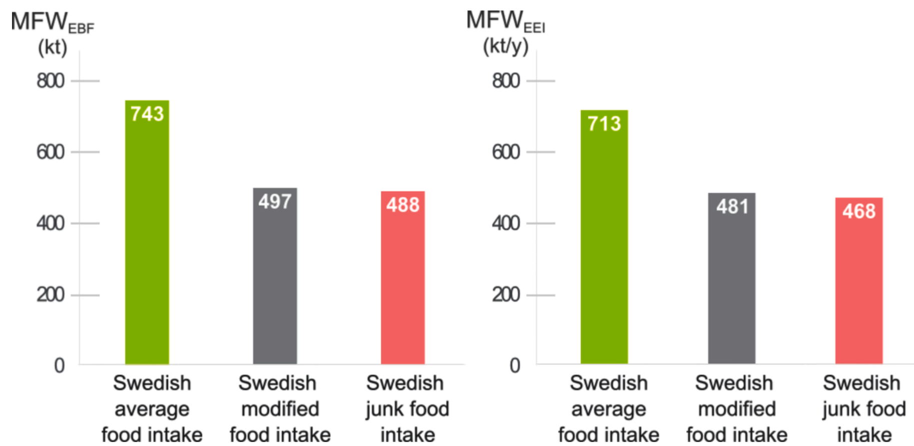

Fig. 1. Total amounts of metabolic food waste corresponding to excess body fat (MFW_{EBF}) (kt) and excess energy intake (MFW_{EEI}) (kt/y) per food intake scenario.

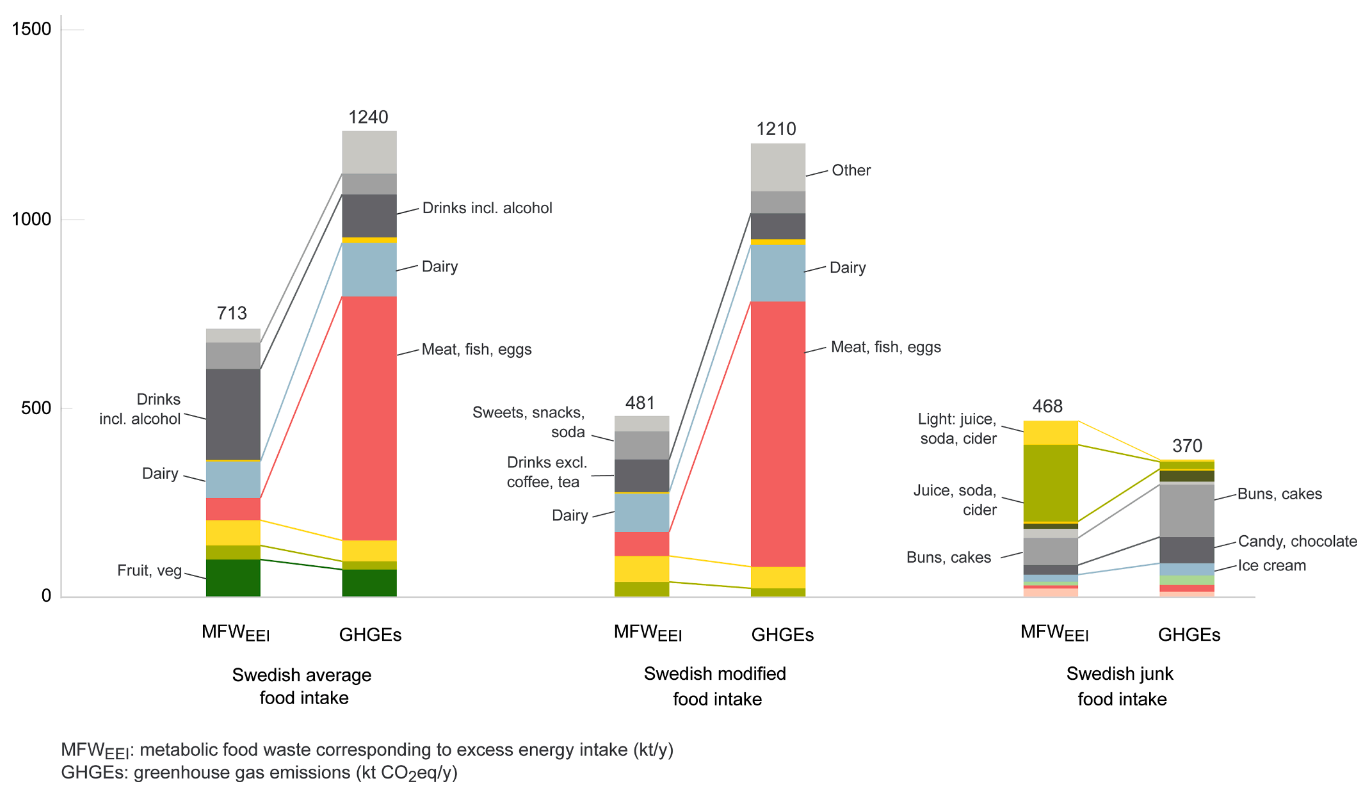

Fig. 2. Annual amount of metabolic food waste corresponding to excess energy intake (MFW_{EEI}) and its climate impact by three food intake scenarios. The results are illustrated by aggregated food groups, where the three food groups contributing most to the results in each scenario are indicated.

excluding coffee and tea); and 3) *sweets, snacks, and soda* (Fig. 2). For the *Swedish junk food intake* scenario, consisting of sweets, snacks, and soda only, MFW_{EBF} amounted to 118 kg per person and 488 kt of food in total for the Swedish adult population, while MFW_{EEI} was 113 kg per person and year and 468 kt of food per year in total. The food groups contributing most to MFW_{EEI} were, in descending order: 1) *juice, soda, and cider*; 2) *buns and cakes*; and 3) *light juice, soda & cider* (Fig. 2).

3.3. Climate impact of metabolic food waste

The climate impact results are presented based only on MFW_{EEI}, due to the similarity of the results for MFW_{EEI} and MFW_{EBF} (Fig. 2). The magnitude of the climate impact based on MFW_{EEI} did not always reflect the amount of MFW_{EEI} when comparing the three dietary scenarios to each other (Fig. 2). Similarly to metabolic food waste, the *Swedish average food intake* scenario gave the highest results in terms of GHGEs. However, the *Swedish modified food intake* scenario resulted in as high a level of GHGEs as the *Swedish average food intake* scenario, while the *Swedish junk food intake* scenario resulted in the lowest amount of GHGEs. In fact, the GHGEs of the *Swedish modified food intake* scenario exceeded the emissions of the *Swedish junk food intake* scenario by more than three-fold, despite both scenarios resulting in similar quantities in terms of metabolic food waste.

The food groups contributing most to the climate impact in the scenarios varied to some degree, although the largest GHGE contributors were in most cases animal-based food commodities. The *Swedish average food intake* scenario resulted in 1280 kt of CO_2e based on MFW_{EBF} in the Swedish adult population, while the result based on MFW_{EEI} was 1240 kt CO_2e per year. The food groups contributing most to the climate impact were, in descending order: 1) *meat, fish and eggs*; 2) *dairy*; and 3) *drinks* *including alcohol* (Fig. 2). The *Swedish modified food intake* scenario resulted in 1240 kt of CO_2e based on excess body fat, and in 1210 kt of CO_2e per year based on excess energy intake, in the Swedish adult population. The food groups contributing most to the climate impact were, in descending order: 1) *meat, fish, and eggs*; 2) *dairy*; and 3) *other* (e.g. *pizza and pie)* (Fig. 2). The *Swedish junk food intake* scenario resulted in 390 kt of CO_2e based on excess body fat, and in 370 kt of CO_2e per year based on excess energy intake, in the Swedish adult population. The food groups contributing most to the climate impact were, in descending order: 1) *buns and cakes;* 2) *candy and chocolate;* and 3) *ice cream* (Fig. 2).

Lastly, metabolic food waste and its climate impact exceeded the amount of avoidable household food waste and its climate impact in Sweden (Fig. 3). In order to harmonize methodologies while conducting the comparison, the GHGE results in the present study were only adjusted with retail FW%, and not with consumption FW%.

4. Discussion

In the present study, the amount of metabolic food waste and its climate impact in Sweden was assessed by two methods and according to three dietary scenarios. The results indicated that the annual amount of metabolic food waste exceeds the total annual amount of avoidable household food waste by up to 66%, representing a significant amount of food waste among the Swedish adult population due to excess food intake (Swedish Environmental Protection Agency, 2020). These results are in line with those in a previous study, where excess food intake was estimated to be at least as high as consumer food waste globally (Alexander et al., 2017). Assuming that two of the scenarios analyzed, *Swedish average food intake* and *Swedish modified food intake*, are closer representations of the actual excess food intake in Sweden than the *Swedish junk food intake* scenario, the results suggest that the corresponding climate impact accounts for approximately 2% of the annual GHGEs of 55 Mt CO_2e in Sweden (Eurostat, 2020). To put the result into further perspective, food production and consumption in Sweden is estimated to be responsible for 20–25% (or roughly 11–14 Mt CO_2e) of the total annual GHGEs in Sweden (Swedish Environmental Protection Agency, 2020). Hence, the annual excess food intake may account for roughly up to 10% of the food-related GHGEs in Sweden. Furthermore, the total annual climate impact of the aforementioned scenarios exceeds the climate impact of avoidable household food waste in Sweden, although there are minor methodological differences in the calculation. Considering the current efforts aimed at reducing avoidable household food waste in Sweden, the European Union, and globally, in order to reduce GHGEs (European Commission, 2016.; Swedish Food Agency et al., 2018), the present results show that excess food intake is a factor to be considered not only in relation to its negative health consequences, but also in climate change mitigation.

The metabolic food waste results varied depending on the dietary scenario. The *Swedish average food intake* scenario resulted in the largest mass of metabolic food waste, whereas the *Swedish modified food intake* and *Swedish junk food intake* scenarios both resulted in approximately 30% lower metabolic food waste mass. The difference may be explained by the *Swedish average food intake* scenario containing more food groups and items low in energy density, such as coffee, tea, vegetables, and fruit, in comparison with the other two scenarios, where such food items were excluded completely.

In comparison with a similar study by Serafini et al. (2016), the *Swedish modified food intake* scenario, based on similar food intake patterns, resulted in approximately 30% higher MFW_{EBF} mass per person with OW and OB. The difference may again be explained by the differences in energy density between foods included in the dietary intake patterns, as Serafini et al. (2016) reported larger proportions of highly energy-dense foods such as meat, alcohol and added fats, but for example no dairy, which was the largest contributor to metabolic food waste in the *Swedish modified food intake* scenario. A further explanation may be a difference in the prevalence of OW, as the present study reported slightly higher average excess body fat. In summary, the determinants of the amount of metabolic food waste are prevalence of OW and OB and the composition of metabolic food waste, i.e., food intake patterns, which may differ from nation to nation.

Further, the results showed that the climate impact of metabolic food waste varied between the dietary scenarios, an effect largely explained by the degree of animal-based foods, especially from ruminants. Previous studies have shown that production of livestock is associated with high GHGEs, especially in the case of ruminants due to their methane production (Scholz et al., 2015). The *Swedish junk food intake* scenario did not include meat, whereas the *Swedish average food intake* and *Swedish modified food intake* scenarios did, resulting in more than three-fold higher GHGEs. Even in the *Swedish junk food intake* scenario, the foods most contributing to the GHGEs contained dairy ingredients (e.g., buns, chocolate, and ice cream).

Although a reduction in animal-based foods and an increase in plant-based foods is often viewed as a necessity for a shift towards environmentally sustainable diets (Willett et al., 2019), our results suggest that dietary scenarios associated with lower GHGEs, such as the *Swedish junk food intake* scenario, may not necessarily be healthier. In fact, previous

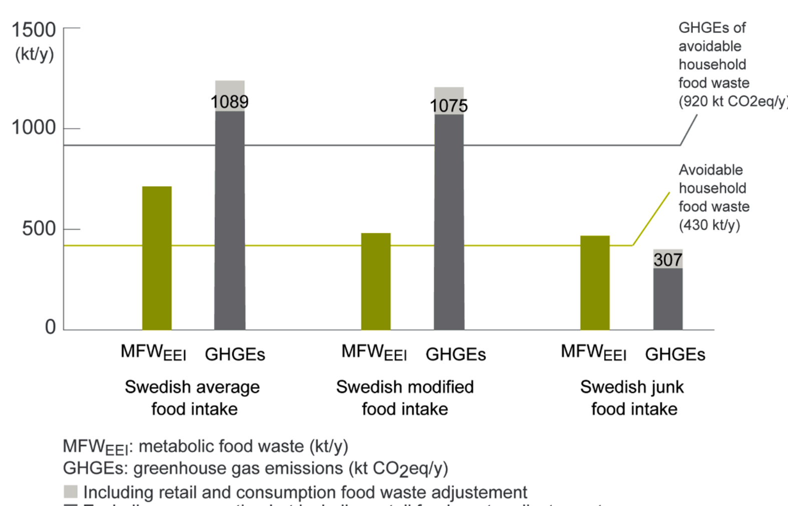

Fig. 3. Metabolic food waste and its climate impact in relation to avoidable household food waste in Sweden. The greenhouse gas emissions (GHGEs) results are presented excluding consumption, but including retail food waste percentage (FW%) adjustment, in order to make the results more comparable to the climate impact of avoidable household food waste. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

reports have highlighted the risk of low climate impact diets being high in sugar (Payne et al., 2016; Vieux et al., 2013). The results of the present study indicate the importance of reducing overall excess food intake for its climate impact, regardless of the composition and quality of foods overeaten, but from a climate perspective a reduction in overconsumption of meat and dairy would be most effective. However, this has to be integrated with the perspective of diet quality since, by definition, sustainable diets not only entail low environmental impact but are also healthy (FAO and WHO, 2019). Therefore, combining both nutritional quality and environmental impact of food choices is fundamental when considering excess food intake.

Previous studies have applied various methods for estimating the caloric value of excess food intake and the foods it comprises. However, to the best of our knowledge, no previous study has attempted to quantify both excess body fat and excess energy intake to estimate climate or any other environmental impact, or to compare the two methods. Although both methods resulted in similarly large quantities of metabolic food waste generated in Sweden, there are some important differences in the methods to be considered. First, the unit of excess body fat is mass, thus revealing no information on how long the body fat has taken to accumulate, which may lead to challenges in interpreting the results. Serafini et al. (2016) suggest addressing this issue by assessing metabolic food waste in epidemiological studies to measure the rise in OB and calculating the environmental impact over time. While this may work, estimates of the climate impact of excess food intake over time could also be based on MFW_{EEI} (Edwards and Roberts, 2009; Porter and Reay, 2016). As the calculation of excess energy intake is based on the extra energy a body requires to maintain existing excess body fat over time (Hall et al., 2011), the unit of MFW_{EEI} is mass/time. Measurements expressed in relation to time are easier to interpret and comparable with other measurements. More importantly, with MFW_{EBF} and MFW_{EEI} measuring different aspects of metabolic food waste, the results of the present study indicate that an amount closely equivalent to the total MFW_{EBF} is generated every year as MFW_{EEI}, risking a considerable annual amount of metabolic food waste going unnoticed if not measured as MFW_{EEI}. Therefore, MFW_{EEI} may be the best-suited method for estimation of metabolic food waste and its environmental impact.

This study suffered from some limitations. Since data on the actual food intake of the adult population with OW and OB in Sweden are lacking, a modeling approach was used to convert the caloric amounts of excess body fat and excess energy intake into metabolic food waste based on three possible dietary scenarios. The dietary scenarios were chosen to represent two opposite alternatives of the excess food intake (Swedish average and Swedish junk food intake), and a more likely scenario in between the two, Swedish modified food intake, following an excess food intake pattern suggested by a previous study (Serafini et al., 2016). The inclusion of the scenarios may be considered as sensitivity analyses of the input data of excess food intake, where especially the climate impact results between the Swedish junk food intake and the other two scenarios differed. Considering that, the excess food intake does not likely consist of junk foods only, but a mixture of all types of energy-dense foods, the results suggest that the true results may lie closer to the Swedish modified food intake. However, since the dietary scenarios were calculated based on the national average food intake of the whole adult population, including people with NW (Amcoff et al., 2012), the proportions of the foods included in the food intake scenario are a further uncertainty requiring caution when interpreting the results.

Further, food-recording methods used in national food surveys often contain limitations per se, such as lack of specific foods (e.g., oils) or poor detail on meal ingredients and preparation methods, which may add to the uncertainty in the data. Moreover, the prevalence statistics of OW and OB were based on self-reported data on body weight and height. Self-reporting of body weight has been associated with under-reporting, especially among subjects with OB, while self-reporting of height has been associated with over-reporting (Gibson, 2005), possibly leading to slightly underestimated excess body fat and excess energy intake in the present study. Further, it has been shown that BMI tends to underestimate rather than overestimate body fatness, which could cause further underestimation of excess body fat and excess energy intake (Okorodudu et al., 2010). Due to lack of data, the same physical activity level value of 1.6 was assumed for all the BMI groups in this study, although there may be differences in physical activity levels between the groups. For example, if the population with OB had a physical activity level of 1.5, the excess energy intake results would be slight overestimates. Considering all these limitations, the results in the present study, especially concerning MFW_{EBF} and its climate impact, could be underestimates. Lastly, it should be noted that the significance of metabolic food waste and its climate impact is underestimated when compared with avoidable household food waste due to household waste amounts including food waste from the entire Swedish population, whereas metabolic food waste is based on the adult population only. Although OW and OB affect a smaller proportion of the child population than of the adult population, its prevalence is increasing in all age groups, children included (Public Health Agency of Sweden 2020a, 2020b). In conclusion, future research based on OW and OB data, and on food intake data for the entire population with OW and OB, is needed to confirm the results of the present study.

Carbon footprints were obtained from a database rather than been ad hoc extracted from the literature for this study. It is therefore important to take into consideration both the heterogeneity of the underlying data and the high variability, which is intrinsic in the LCA methodology (i.e. carbon footprint estimates can be highly variable depending on geography, seasonality, method of production, the energy source for processing, etc.), when analyzing the results from this study. The results should therefore be interpreted as approximate providing an estimate of the magnitude of the climate impact associated with excess food intake, rather than exact. Moreover, the carbon footprints did not include GHGEs related to packaging or homebound transportation of food from grocery stores. While not the major contributors of GHGEs in the food supply chain, the exclusion of the aforementioned emissions could cause a slight underestimation of the results.

The present study included climate as the only environmental impact category when estimating the impact of excess food intake in Sweden. Nevertheless, excess food intake likely also contributes negatively to other environmental impacts, such as depletion of freshwater sources, land-use change, and loss of biodiversity, which could also be estimated by using the methodology of the present study (Crenna et al., 2019; Moberg et al., 2020; Springmann et al., 2018). In addition, while junk foods made a less significant negative contribution to climate impact in the present study, they could make a greater contribution if other environmental impacts were investigated. The use of scarce resources for producing ultra-processed foods with low nutritional value that contribute to OB and ill health seems unjustified in today's world, which is in need of sustainable food systems (Hadjikakou and Bake, 2020).

The results of the present study highlight the magnitude of metabolic food waste and its climate impact as an avoidable environmental burden. Although the results are based on data specific to Sweden, other countries with similar demographics and food cultures are likely to have similar results due to the connection between the amount of metabolic food waste and the prevalence of OW and OB. Additionally, the methodology applied in this study, which for the first time used and compared two different methods to estimate the metabolic food waste, can be replicated in other countries enabling more international studies assessing the environmental impact of excess food intake. The high prevalence of OW and OB is a major global issue, for adults and children alike, and due to the challenges in treating OB, its prevention is of the highest importance (Nittari et al., 2019; Vorkoper et al., 2021; WHO; 1999). However, despite the serious efforts to reverse the OW and OB epidemic for the past three decades, the prevalence is increasing throughout the globe (Swinburn et al., 2019; WHO, 2020b). While reasons for this may be various from a lack of political will to a lack of public interest in solving the issue, OB has also largely been treated in isolation from other global challenges (Lawrence and Friel, 2020; Swinburn et al., 2019). Simultaneously, the urgency of solving the global climate issue is widely recognized, with an increasing amount of mitigation agreements and action plans on all levels (European Commission, 2016; Swedish Food Agency et al., 2018; UNFCCC, 2021). However, excess food intake, or metabolic food waste, is currently not addressed in plans for higher environmental sustainability, such as food waste reduction plans for mitigating climate impact. Yet, linking metabolic food waste together with environmental sustainability and public health as means to support policymaking could come with benefits (Lawrence and Friel, 2020). Combining the issues could be a way not only strengthening the efforts needed in solving them, but also to provide an opportunity for synergies while doing so.

Conclusions

In conclusion, MFW_{EEI} exceeded the total amount of annual avoidable household food waste, indicating a significant amount of continuous food wastage due to the excess food intake in Sweden. Further, the climate impact of the excess food intake accounted for up to 2% of the total and 10% of the food-related annual GHGEs in Sweden, depending on the proportion of animal-based foods. The present study confirms the magnitude of the hidden climate cost of excess food intake and presents a method for estimating its extent that can be applied internationally to further transform food systems. Food systems are dynamic and complex due to their interconnections with other systems, such as economic, social, and political, where changes in one system affect the others. While metabolic food waste only occurs at the consumer stage, its successful reduction due to a collective dietary change would require changes and adaptation throughout the whole food system. Such changes, such as taxation on sugary drinks or re-designed junk food campaigning strategies, have proven challenging in the past as interventions proposed to change food systems for better health and environmental outcomes often receive strong responses from the business and even the public (Swinburn et al., 2019). Environmental or climate implications of such food system transformation were neither captured by the methodology nor included in the scope of the present study and therefore further studies are warranted. Further, as highlighted by the results of the present study, there is a need to prioritize global interventions to reduce excess food intake as a means to benefit both human and planetary health. To achieve the above, joint efforts involving all stakeholders along the food supply chain will be necessary. The awareness that up to 10% of food-related GHGEs in a westernized country like Sweden are avoidable, and the potential that addressing these emissions could have for both global planetary and human health, should further drive the transformation of food systems.

Author contributions

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All authors have read and agreed to the published version of the manuscript.

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.

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Supplementary materials

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