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LETTER

Lost water and nitrogen resources due to EU consumer food waste

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Abstract

The European Parliament recently called for urgent measures to halve food waste in the EU, where consumers are responsible for a major part of total waste along the food supply chain. Due to a lack of data on national food waste statistics, uncertainty in (consumer) waste quantities (and the resulting associated quantities of natural resources) is very high, but has never been previously assessed in studies for the EU. Here we quantify: (1) EU consumer food waste, and (2) associated natural resources required for its production, in term of water and nitrogen, as well as estimating the uncertainty of these values. Total EU consumer food waste averages 123 (min 55–max 190) kg/capita annually (kg/cap/yr), i.e. 16% (min 7–max 24%) of all food reaching consumers. Almost 80%, i.e. 97 (min 45–max 153) kg/cap/yr is avoidable food waste, which is edible food not consumed. We have calculated the water and nitrogen (N) resources associated with avoidable food waste. The associated blue water footprint (WF) (the consumption of surface and groundwater resources) averages 27 litre per capita per day (min 13–max 40 l/cap/d), which slightly exceeds the total blue consumptive EU municipal water use. The associated green WF (consumptive rainwater use) is 294 (min 127–max 449) l/cap/d, equivalent to the total green consumptive water use for crop production in Spain. The nitrogen (N) contained in avoidable food waste averages 0.68 (min 0.29–max 1.08) kg/cap/yr. The food production N footprint (any remaining N used in the food production process) averages 2.74 (min 1.02–max 4.65) kg/cap/yr, equivalent to the use of mineral fertiliser by the UK and Germany combined. Among all the food product groups wasted, meat accounts for the highest amounts of water and N resources, followed by wasted cereals. The results of this study provide essential insights and information on sustainable consumption and resource efficiency for both EU policies and EU consumers.

1. Introduction

Global food security will be one of mankind's main challenges this century. A key question is whether humanity has the natural resource base to feed itself equitably and sustainably both now and in the future. Currently, 842 million people are chronically undernourished [1], while 1.46 billion adults are overweight, of whom 502 million are obese [2]. Within the EU, 227 million (58% of all) adults are overweight, of whom 91 million (23% of all adults) are obese [3, 4]. By 2050, a projected 9–10 billion people should be provided with a healthy diet in a sustainable way [5]. In creating a more sustainable food system, solutions need to combine demand-side and supply-side options [6]. Demand-side solutions should target dietary habits as well as food waste [7–9]. This paper focuses on food waste.

According to the UN's Food and Agriculture Organization (FAO) [8], roughly one-third of food produced for human nutrition is either lost or wasted globally, which amounts to approximately 1.3 billion tonnes per year. Food is lost or wasted throughout the entire supply chain, from initial agricultural production down to final household consumption. In industrial countries, the fraction of food wasted by consumers of the total food lost and wasted is high. According to this FAO study [8], the food wasted per-capita by consumers in Europe and North America is about 95 to 115 kg yr^{-1}. Total per-capita food loss and waste along the entire supply chain in Europe and North America is 280–300 kg yr^{-1}. Thus, consumer food waste represents about one-third of this amount. A study on consumer food waste in the EU-27 [10] quantified total food waste per capita at 101 kg yr^{-1} (76 kg yr^{-1} for households and 25 kg yr^{-1} for the food service/catering sector).

An essential limitation of previous quantification studies on consumer food waste for Europe—e.g. [8] or the EU—e.g. [10, 11]—is that they only use one value (total and/or per product/product group), thereby not taking into account the uncertainty and lack of reliable data on food waste statistics. The FAO study [8] on food losses and waste only uses UK data for consumer food waste in Europe [12]. The study on food waste carried out on behalf of the European Commission [10] quantifies total consumer food waste for each EU Member State based on assembled statistical data, but gives no range on uncertainty and does not differentiate between product groups. A recent study on behalf the European Parliament [13] acknowledges that the estimations in the latter study are conservative, and probably underestimate.

A number of studies have quantified particular natural resources (including energy [14]) associated with food waste, often by means of environmental footprints, the latter being an umbrella term for the different footprint concepts that have been developed during the last two decades [15]. Well-established footprint indicators include the water footprint (WF) [16], nitrogen footprint (NF) [11, 17, 18], land footprint (LF) [19] and carbon footprint (CF) [20]. The WF is an indicator of direct and indirect water use. The concept has been introduced into water-management science to show the importance of consumption patterns and the global dimensions of good water governance [16]. The NF comprises the sum of the nitrogen contained in food (based upon protein content) and the food production NF. The LF measures the appropriation of land as a resource. The CF measures the emission of greenhouse gases (GHGs) into the atmosphere. For example, Chapagain and James [21] calculated the WF and CF of household food and drink waste in the UK. The FAO [22] quantified the CF, WF and LF of global food wastage (i.e. both food loss and food waste). Kummu *et al* [23] quantified the WF as well as the cropland and fertiliser use associated with food wasted on a global level.

The aim of this study was to quantify EU consumer food waste, taking account of uncertainty. In particular, we have quantified not only the total amount of food waste but also the food waste per product group. We have also differentiated between total food waste and avoidable food waste. In addition, we have quantified the associated natural resources required for the production of this food waste, in terms of water and nitrogen. For this, we have used the WF and NF concepts. We chose these two footprints as they are well established and because detailed studies have been made on the WF and NF of EU food production and consumption [9, 24–26]. Future research should include additional resources/footprints.

2. Methodology

2.1. General

We have quantified consumer food waste for the EU-28 with the associated uncertainty. We have analysed average annual values for the period 1996–2005. During this period, the average population of the EU was 487 million. The methodology is presented below and an overview of the workflow of the methodology is given in figure 1, with explanations of the abbreviations used throughout the manuscript provided in table 1.

2.2. Quantification of food consumption data (FOOD_CONS)

As a first step, average EU food consumption data have been quantified by taking food supply quantity data (FOOD_SUPPLY) of different product groups from the FAO Food balance sheets (FBS) [27]. These provide data on the amount of food that reaches the consumer in private households, as well as that in the non-household sector, i.e. catering establishments, boarding schools, hospitals, prisons, armed forces' bases and other communities. The data are given on an 'as purchased' basis, i.e. as the food leaves the retail shop or enters the household by other means.

Quantities are provided on the basis of 'primary equivalents'. Within the FAO FBS, food data are standardized in that processed commodities are converted back to their 'primary equivalent'. This is for standardization (different countries report their data to the FAO), simplification and limitation of the number of commodities within the FBS. The latter implies that it is beneficial to reduce the amount of data, and therefore the number of commodities involved, to a level and size more suited to analytical purposes. E.g., instead of listing flour of wheat, bread or pasta separately in the FBS, they are quantified as wheat equivalent. Similarly, meat (reaching consumers in many forms, e.g. for chicken as—amongst others—a whole chicken, chicken filet, sausages or chicken nuggets) is quantified as carcass weight in the FBS.

We have estimated food consumption at the point where it reaches the consumer, using a first correction factor (CORR1) which accounts for product primary equivalent conversion (equation (1)). To calculate total and avoidable wasted food quantities from FOOD_SUPPLY, two correction factors are applied. The first factor (CORR1) accounts for product primary equivalent conversions (equation (1)) and the second for food waste (CORR2).

The specific values for CORR1 have been taken from [28]. For example, the CORR1 of wheat equivalent is 0.8, as only 80% of the original wheat weight

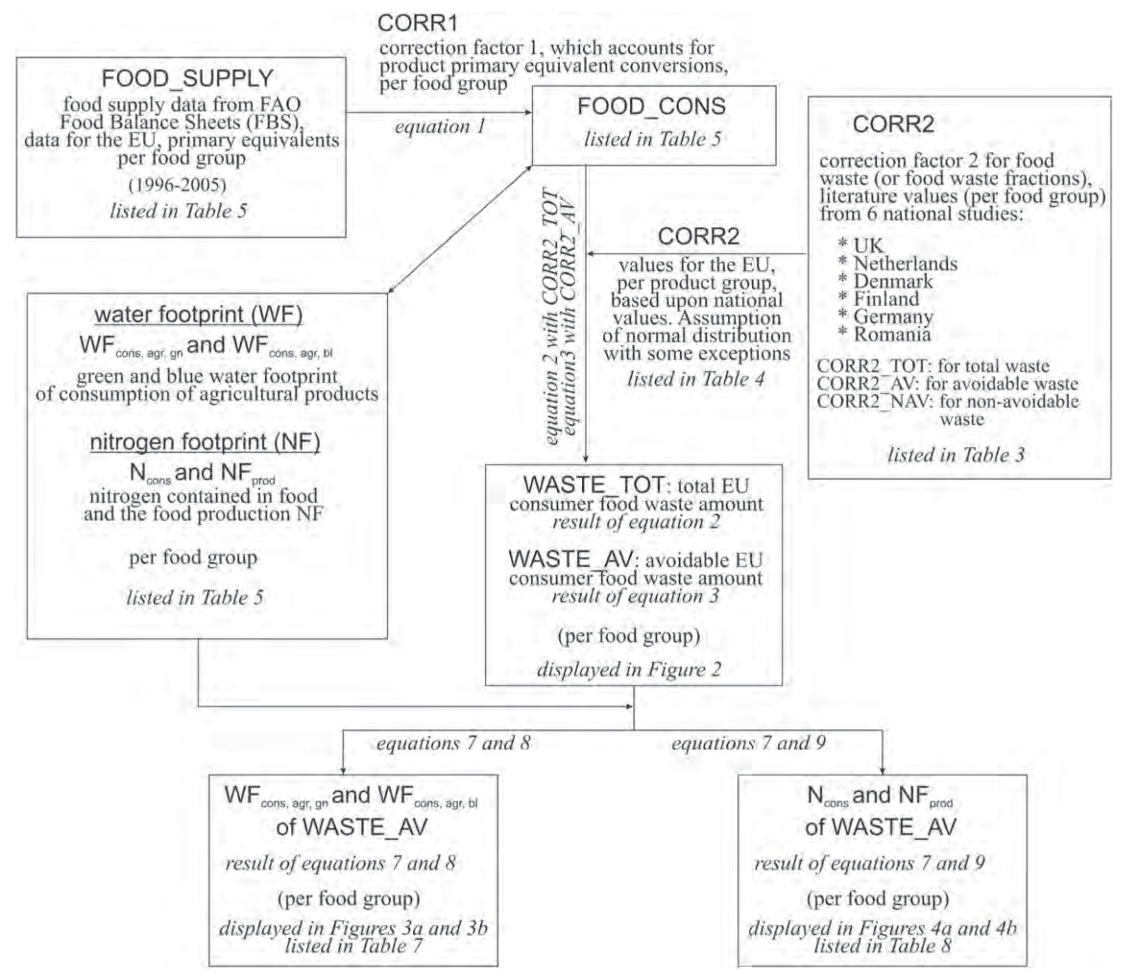

Figure 1. Workflow of the methodology; the equations are listed in table 2.

Table 1. Abbreviations used in the letter.

Abbreviation	Definition
EU	European Union
WF	Water footprint
WF_{prod}	Water footprint of production
WF_{cons}	Water footprint of consumption
$WF_{cons,agr}$	Agricultural water footprint of production
$WF_{cons,agr,gn}$; $WF_{cons,agr,bl}$	Green; blue agricultural water footprint of consumption
NF	Nitrogen footprint
N_{cons}	Nitrogen contained in food
NF_{prod}	Food production NF
FAO	Food and Agriculture Organization of the United Nations
FBS	Food balance sheet
FOOD_SUPPLY	Food supply quantity (data)
FOOD_CONS	Food consumption quantity (data)
CORR1	Correction factor 1, which accounts for product primary equivalent conversions
CORR2	Correction factor 2, which accounts for food waste
CORR2_TOT	Correction factor 2, which accounts for total food waste
CORR2_AV	Correction factor 2, which accounts for avoidable food waste
CORR2_PA	Correction factor 2, which accounts for potentially avoidable food waste
CORR2_NA	Correction factor 2, which accounts for non-avoidable food waste
WASTE_TOT	Total food waste quantity
WASTE_AV	Avoidable food waste quantity
WASTE-NA	Non-avoidable food waste quantity
DEFRA	UK Department for Environment, Food & Rural Affairs
Mt	Million tonnes
l/cap/d	Litre per capita per day

Table 2. Equations used to compute waste amounts (equations (1)–(6)) and related resources (equations (7)–(9)).

FOOD_SUPPLY × CORR1 =		FOOD_CONS	(1)
with:	FOOD_SUPPLY =	Food supply quantity as given in FAO Food Balance Sheets (FBS). Food supply is food (in tonnes) reaching the consumer, i.e. in private households, as well as the food service/catering sector	
	CORR1 =	Correction factor 1, which accounts for product primary equivalent conversions	
	FOOD_CONS =	Food consumption.	
FOOD_CONS × CORR2_TOT =		WASTE_TOT	(2)
FOOD_CONS × CORR2_AV =		WASTE_AV	(3)
FOOD_CONS × CORR2_NA =		WASTE_NA	(4)
With:	CORR2 =	Correction factor 2, which accounts for food waste	
	CORR2_TOT =	Correction factor 2, which accounts for total food waste	
	CORR2_AV =	Correction factor 2, which accounts for avoidable food waste	
	CORR2_NA =	Correction factor 2, which accounts for non-avoidable food waste	
	WASTE_TOT =	Amount of total consumer food waste	
	WASTE_AV =	Amount of avoidable consumer food waste	
	WASTE_NA =	Amount of non-avoidable consumer food waste	
WASTE_TOT =		WASTE_AV + WASTE_NA	(5)
FOOD_CONS =		INTAKE + WASTE_TOT	(6)
With:	INTAKE =	Amount of food actually consumed	
$\text{WASTE\_AV}_{\text{CORR}}$ =		$\frac{\text{WASTE\_AV}}{1-\text{CORR2\_NA}}$	(7)
with	$\text{WASTE\_AV}_{\text{CORR}}$ =	Corrected amount of avoidable consumer food waste to relate to the resource footprint (WF or NF) of WASTE_AV	
	CORR2_NA =	$\frac{\text{WASTE\_NA}}{\text{FOOD\_CONS}}$ as obtained from (1) and (4):	
$\text{WF}_{\text{cons,agr}}$ of WASTE_AV =		$\left(\frac{\text{WASTE\_AV}_{\text{CORR}}}{\text{FOOD\_CONS}}\right) \times \text{WF}_{\text{cons,agr}}$	(8)
with	$\text{WF}_{\text{cons,agr}}$ =	$\text{WF}_{\text{cons,agr}}$ of FOOD_CONS	
NF of WASTE_AV=		$\left(\frac{\text{WASTE\_AV}_{\text{CORR}}}{\text{FOOD\_CONS}}\right) \times \text{NF}$	(9)
With	NF =	NF of FOOD_CONS	

remains after conversion to wheat flour. In addition to the first factor values listed in the latter publication, 7.4 milk equivalent has been taken for cheese, as obtained from [3], 7 milk equivalent for cream, and 1 milk equivalent for yoghurt. After applying CORR1, food consumption data (FOOD_CONS) have been quantified.

2.3. Quantification of food waste amounts

Total and avoidable quantities of wasted food from FOOD_SUPPLY have been obtained by applying a second correction factor for food waste (CORR2) on food consumption quantities (FOOD_CONS). This factor relates either to total food waste (CORR2_TOT) or to avoidable food waste (CORR2_AV), as we have differentiated between total (WASTE_TOT) and avoidable (WASTE_AV) food waste. The latter excludes non-avoidable food waste (WASTE_NA) such as meat bones, egg shells, fruit stones or the peel of certain fruit and vegetables. Avoidable food waste means food that at some point prior to disposal was edible. The relevant equations (2)–(6) are listed in table 2 below.

Based upon FOOD_CONS, total (WASTE_TOT, equation (2)) and avoidable food (WASTE_AV, equation (3)) waste quantities are thus calculated by means of CORR2_TOT and CORR2_AV. Non-avoidable food waste (WASTE_NA) is the difference between WASTE_TOT and WASTE_AV (equation (5)).

CORR2_TOT and CORR2_AV values have been obtained for the product groups from/based upon six selected national studies, i.e.

- the UK [29],
- the Netherlands [30],
- Denmark [31],
- Finland [32],
- Germany [33],
- Romania [34].

For other EU countries, either no data were found or they were unreliable. These values are shown in table 3 below.

Only estimations of household waste have been quantified in these studies. For the non-household (food service/catering) sector part of FOOD_CONS, the same CORR2 values have been taken.

The most detailed assessment was done in the UK [29] for the year 2007 (a field study of over 2000 households), where a distinction is made between avoidable waste, potentially avoidable waste and unavoidable waste. Where purchased amounts of specific products or product groups are missing, DEFRA (the UK's Department for Environment, Food & Rural Affairs) statistics have been used. Apart from avoidable and non-avoidable food waste, the UK study also

Table 3. Estimates of food waste fractions (CORR2 in %) of household food purchases (FOOD_CONS) by food group, based upon literature values.

	UK [29]				The Netherlands, based upon [30]			Denmark, based upon [31]			Finland [32]	Germany, based upon [33]		Romania [34]
Product group	CORR2_AV	CORR2_PA	CORR2_NA	CORR2_TOT	CORR2_AV	CORR2_NA	CORR2_TOT	CORR2_AV	CORR2_NA	CORR2_TOT	CORR2_AV	CORR2_AV	CORR2_TOT	CORR2_AV
Cereals	26	3	0	29	12	0	12	12	1	13	13	11–15		>0 and <10
Potatoes	17	28	0	45	5	4	9				19			
Vegetables	23	13	9	45	9	11	20	5	11	16	19	15–20	18–23	>0 and <10
Fruit	19	3	19	41	9	16	25	5	11	16	13	8–10	18–23	>0 and <10
Sugar														
Pulses, nuts and oil crops														
Crop oils	4	12[a]	1	17										
Animal fats	4	12[a]	1	17										
Stimulants														
Spices														
Alcoholic beverages	5	0	0	5										
Meat	11	3	9	23	6	2	8	5	2	7	7	4–6	11–15	>0 and <10
Fish	11	3	9	23	2	7	9	5	2	7	7	4–6	11–15	>0 and <10
Eggs	5	0	12	17	2	6	8				7			
Milk	7	0	0	7	5	0	5				17	3–4	7–9	>0 and <10
Yoghurt	13	0	0	13	5	0	5				17	3–4	7–9	>0 and <10
Cheese	10	0	0	10	3	1	4				17	3–4	7–9	>0 and <10

[a] In ([29]) the potentially avoidable waste for oils and fats includes all oils and fats which have only been used once—however, this is not recommended in other countries, therefore a second use is discarded in this analysis and the potentially avoidable waste proportion reduced to 0%.

Table 4. Statistical normal distribution values (av = average; stdev = standard deviation; max = maximum; min = minimum) of total and avoidable food waste fractions (CORR2_TOT and CORR2_AV in %), based upon the literature values in table 3. For sugar, stimulants, spices and alcoholic beverages, correction factors are assumed to be uniformly distributed.

	Total waste				Avoidable waste			
Product group	av	stdev	max	min	av	stdev	max	min
Cereals	17.12	8.6	29	5	17.12	8.6	29	5
Potatoes	25.5	14.2	45	5	25.2	15	45	5
Sugar			10	5			10	5
Pulses	5	1.8	7	2	4.7	1.9	7	2
Crop oils	5	1.8	7	2	4.7	1.9	7	2
Vegetables	26.2	13.9	45	5	20.9	11.5	36	4
Fruit	25.5	12	41	5	12.6	6.8	22	4
Stimulants			10	5			10	5
Spices			10	5			10	5
Alcoholic beverages			7	3			7	3
Meat	14.5	6.6	23	4	7.7	4.6	14	2
Animal fats	5	1.8	7	2	5	1.8	7	2
Eggs	11.9	3.9	17	6	5.1	1.8	7	2
Milk (and yoghurt)	7	2.8	17	2	5.2	3	17	2
Cheese	7.9	3.2	17	2	6	3.9	17	2
Cream	5.2	3	17	2	5.2	3	17	2
Fish	14.5	6.5	23	4	7.4	4.8	14	2

identifies potentially avoidable food waste. However, in our study we have added this fraction (CORR2_PA) to avoidable food waste (CORR2_AV) for the UK statistics, as other national studies do not account for potentially avoidable food waste.

Table 3 shows that for some product groups detailed statistics are available for several countries, e.g. for cereals, vegetables, fruit, meat, milk and milk products. For other product groups, statistics are only available for selected countries (e.g. alcoholic beverages or crop oils) and for some product groups, no statistics are available (e.g. sugar or stimulants). The data compiled in table 3 show that for all product groups: (1) CORR2_TOT and CORR2_AV values are highest in the UK (except for milk/milk products where Finland has a higher value); and (2) CORR2_AV values are amongst the lowest in Romania. To account for any uncertainty in the estimations, we have assumed that Romania represents the minimum CORR2 values and the UK the maximum values for EU countries, and that all other values are between these two extremes. Schneider [35] has already pointed out that in Europe, the proportion of household expenditure on food is highest in Eastern Europe (e.g. 44.2% in Romania) and that this might be expected to have a significant impact on food waste behaviour. The UK has already been identified as the EU country with the highest per capita consumer food waste [10].

To compute the CORR2_TOT and CORR2_AV distributions for the EU, based upon the six selected national studies, we have made some assumptions. In particular, we have assumed that the correction factors (CORR2_TOT and CORR2_AV) per product group to calculate WASTE_TOT and WASTE_AV are distributed normally. Their means and standard deviations (as shown in table 4 below) were calculated from the available country data (table 3). To calculate these mean EU values from the six national values, these national values are weighted according to national populations. For example, the values for Germany are weighted at 43% and those of the Netherlands at 8%. For sugar, stimulants, spices and alcoholic beverages the associated correction factors were assumed to be uniformly distributed, as detailed data are missing.

2.4. Quantification of related water resources (the water footprint or WF)

In our study, we used the WF concept. For the purpose of water resources management (e.g. in the EU, as in our study), a geographical WF assessment is relevant. It is important to distinguish between the WF of production (WF_{prod}) and the WF of consumption (WF_{cons}) of a region [16]. The first refers to the total use of domestic water resources within the region (for producing goods and services for domestic consumption or export). The second refers to the use of domestic and foreign water resources behind all the goods and services consumed domestically.

Dependent on the authors, a WF comprises either three (blue, green and grey) or two (blue and green) components. As defined in [36], green water is the soil water retained in the unsaturated zone, which is formed by precipitation and is available to plants; blue water refers to water in rivers, lakes, wetlands and aquifers. Irrigated agriculture receives blue water (from irrigation) as well as green water (from precipitation), while rain-fed agriculture only receives green water. Thus, the green WF is the rainwater consumed by crops. The grey WF is an indicator of the

Table 5. Average annual (1996–2005) FOOD_SUPPLY and FOOD_CONS values (in kg/cap/yr) of different product groups for the EU. The $WF_{cons,agr,gn}$ and $WF_{cons,agr,bl}$ (in l/cap/d) and the N_{cons} and NF_{prod} (in kg/cap/yr) are also shown.

Product group	FOOD_SUPPLY (kg/cap/yr)	FOOD_CONS (kg/cap/yr)	Green $WF_{cons,agr}$ (l/cap/d)	Blue $WF_{cons,agr}$ (l/cap/d)	N_{cons} (kg/cap/yr)	NF_{prod} (kg/cap/yr)
Cereals	123.7	93.3	337	21	1.7	1.9
Potatoes	81.9	81.9	33	6	0.2	0.3
Sugar	39.7	39.7	158	30	0.0	0.3
Pulses, nuts and oil crops	10.3	10.3	95	10	0.2	0.1
Crop oils	18.5	18.5	293	23	0.0	0.4
Vegetables	120.8	120.8	47	14	0.2	0.3
Fruit	98.8	98.8	115	30	0.1	0.3
Stimulants	7.5	7.5	322	2	0.1	0.0
Spices	0.5	0.5	9	1	0.0	0.0
Alcoholic beverages	109.3	109.3	84	6	0.1	1.2
Meat	88.5	59.4	1247	82	1.7	18.3
Animal fats	13.3	13.3	103	6	0.0	0.5
Eggs	12.4	12.4	68	4	0.2	0.6
Milk (excluding butter)[a]	234.1 (including cheese, cream and yoghurt)	95.3 (milk and yoghurt)—yoghurt 1 l milk for 1 kg	192	15	0.5	2.6
Cheese[a]	0	15.2 (112.5 milk eq.—7.4 l milk for 1 kg)	227	17	0.6	3.1
Cream[a]	0	3.8 (26.3 milk eq.—7.0 l milk for 1 kg)	53	4	0.1	0.7
Fish and seafood	21.2	8.5	0	0	0.4	1.8
Total	980.5	788.5	3383	270	6.0	32.4

[a] FOOD_CONS values for cheese and cream are taken from FAOSTAT food supply statistics. Milk equivalent (milk eq.) values are computed from EUROSTAT-data.

degree of water pollution [37]. However, many authors perceive this component critically [24, 38, 39].

To quantify the water resources related to these wasted food amounts, we have used the WF of consumption (WF_{cons}) concept [16, 37]. In particular, we have assessed the green and blue WF_{cons} of agricultural products ($WF_{cons,agr}$) for wasted food. Therefore, the $WF_{cons,agr}$ refers to the use of domestic and foreign water resources for all agricultural goods that are consumed domestically. The green $WF_{cons,agr}$ ($WF_{cons,agr,gn}$) represents the consumptive rainwater use for the production of crops and animal products which EU citizens consume. Similarly, the blue $WF_{cons,agr}$ ($WF_{cons,agr,bl}$) represents the consumptive use of water from rivers, lakes and groundwater for this production.

As a first step, the $WF_{cons,agr}$ of FOOD_CONS needs to be quantified. To assess the $WF_{cons,agr}$, we have followed the methodology of the Global Water Footprint Standard developed by the Water Footprint Network [36]. National green and blue $WF_{cons,agr}$ data are accessed from [16, 40] and aggregated to product groups at the EU level. As a result, the blue and green $WF_{cons,agr}$ ($WF_{cons,agr,gn}$ and $WF_{cons,agr,bl}$) of FOOD_CONS are obtained.

As a next step, the $WF_{cons,agr}$ ($WF_{cons,agr,gn}$) and ($WF_{cons,agr,bl}$) of avoidable waste amounts (WASTE_AV) needs to be quantified. To do this, first the unavoidable fraction (CORR2_NA) must be added to WASTE_AV because the $WF_{cons,agr}$ of FOOD_CONS relates to the whole product. Thus we have calculated a new component $WASTE\_AV_{CORR}$ by means of equation (7) (table 2).

When both the $WF_{cons,agr}$ of FOOD_CONS and $WASTE\_AV_{CORR}$ are calculated, the $WF_{cons,agr,gn}$ and $WF_{cons,agr,bl}$ for WASTE_AV are computed using equation (8) (table 2).

To clarify, we present the example of vegetables. Using equation (1), we have calculated the FOOD_CONS value for vegetables as 120.8 kg/cap/yr (table 5). The related $WF_{cons,agr,gn}$ of this amount is 47 l/cap/d (table 5). With an average avoidable food waste fraction (CORR2_AV) of 20.9% (table 4), we have used equation (3) to calculate the average amount of avoidable consumer fruit waste (WASTE_AV) as 25.3 kg/cap/yr.

In order to calculate the $WF_{cons,agr,gn}$ of this avoidable food waste, first we added the unavoidable fraction of the amount of waste. For example, when an onion is wasted the avoidable waste quantity (WASTE_AV) is the onion without its skin. The $WF_{cons,agr,gn}$ of all onions consumed and wasted by EU consumers (FOOD_CONS of onions) relates to the whole product, including the skin. Therefore the skin must be added to the wasted onion to calculate its $WF_{cons,agr,gn}$.

For all vegetables, the corrected avoidable waste amount ($WASTE\_AV_{CORR}$)—which is only useful to calculate the related footprint—is computed by means of equation (7).

$WASTE\_AV_{CORR} = \frac{WASTE\_AV}{1 - CORR2\_NA}$ (equation (7)) $= \frac{25.3}{1-0.053} = 26.7$ kg/cap/yr

with $CORR2\_NA = \frac{WASTE\_NA}{FOOD\_CONS} = \frac{6.4}{120.8} = 0.053$

with WASTE_NA (equation (4)) = FOOD_CONS × CORR2_NA = 120.8 kg/cap/yr × 5.3% = 6.4 kg/cap/yr

The $WF_{cons,agr,gn}$ of avoidable vegetable waste is then calculated using equation (8):

$$\left(\frac{WASTE\_AV_{CORR}}{FOOD\_CONS}\right) \times WF_{cons,agr} = \left(\frac{26.7}{120.8}\right) \times 47\ \text{l/cap/d} = 10.4\ \text{l/cap/d}.$$

2.5. Quantification of related nitrogen resources (the nitrogen footprint or NF)

To quantify the nitrogen resources related to these wasted food amounts, we have used the NF concept [11, 18, 26]. In particular, we have assessed the nitrogen contained in food (N_{cons}) and in food production NF (NF_{prod}) for avoidable food waste. The N_{cons} quantifies the N-content within a product (based upon the protein content). The NF_{prod} is any nitrogen that has been used in the food chain and has been lost to the environment as emissions of nitrous oxide, nitric oxide, ammonia or molecular nitrogen to the atmosphere, or as nitrate or organic nitrogen to the hydrosphere before the food product is supplied to the consumer [26].

To assess the nitrogen intake (N_{cons}) and food production N footprint (NF_{prod}), we have used the data from [26]. The authors have provided NF factors calculated with the CAPRI model for individual crops and applicable to the quantity of food supplied at the farm gate. The data have been aggregated to the FBS crop groups, and NF_{prod} has been scaled to also include the losses of reactive nitrogen linked to wastages that occur between the farm gate and supply to the consumer. The quantity of these wastages is also given in the FBS.

The N_{cons} and NF_{prod} of avoidable food waste are calculated in analogy to the WF, as shown in equation (9) (table 2). Leip *et al* [26] also provide detailed data for the EU on the fate of the N surplus, and thus its potential contribution to adverse environmental impacts and associated damage costs [6, 7, 41–47]. Specifically, the shares emitted into the atmosphere as nitrous oxide (N_2O), ammonia (NH_3), nitrogen oxides (NO_x) or dinitrogen (N_2), or released to the hydrosphere via surface run-off or nitrogen leaching have been calculated on the basis of the life-cycle assessment model implemented in the CAPRI model for GHG accounting [48] and extended to cover nitrogen flows [26]. We have used their database of crop-specific emission unit flows to quantify the emissions of reactive nitrogen associated with food consumption in Europe.

Table 6. Different components of the EU NF_{prod} in kg/cap/yr and Tg/yr (total 32.4 kg/cap/yr or 15.9 Tg yr^{-1} for the EU population). The 'nitrogen leaching and runoff' component is dominant (36.4%), followed by the 'N_2' component (29.3%). These values are comparable with earlier work [45].

	Emissions related to NFprod		Share of total NFprod
	kg/cap/yr	TgN/yr	%
N_2O	0.58	0.28	1.8
NH_3	6.22	3.03	19.2
NO_x	0.19	0.09	0.6
N_2	9.48	4.62	29.3
Nitrogen leaching and runoff	11.78	5.75	36.4
Nitrogen in animal waste and excess manure	4.02	1.96	12.5
Sum	32.35	15.78	100.0

3. Results

3.1. Values for FOOD_CONS

As a first step, we calculated the total amount of food reaching consumers (FOOD_CONS) based upon FAO FBS FOOD_SUPPLY values for different product groups and the related water and NFs. These results are presented in table 5.

More particularly, table 5 shows:

- FOOD_SUPPLY values for the EU for different product groups from the FAO FBS;
- FOOD_CONS values after applying the correction factor CORR1 (equation (1)). All food reaching consumers (FOOD_CONS) equals 789 kg/cap/yr;
- The FOOD_CONS related $WF_{cons,agr,gn}$ and $WF_{cons,agr,bl}$ values (in l/cap/d). The total (sum of all product groups) $WF_{cons,agr,gn}$ amounts to 3383 l/cap/d and the $WF_{cons,agr,bl}$ to 270 l/cap/d. These values have already been presented in [9];
- The N_{cons} and NF_{prod} (in kg/cap/yr) values related to FOOD_CONS. The total (sum of all product groups) N_{cons} amounts to 6.0 kg/cap/yr and the NF_{prod} to 32.4 kg/cap/yr.

The NF comprises N_{cons} and NF_{prod}. Total FOOD_CONS NF_{prod} (N losses to the environment before the food product is supplied to the consumer) amount to 15.8 Tg N yr^{-1}. About 30% of total N losses occur as molecular nitrogen (N_2). They have no adverse effect on the environment and thus represent inefficient resource use [41] (see table 6 below). The 'nitrogen leaching and runoff' component is dominant (36.4%). These values are comparable with earlier work [45]. Up to 13% of the total losses

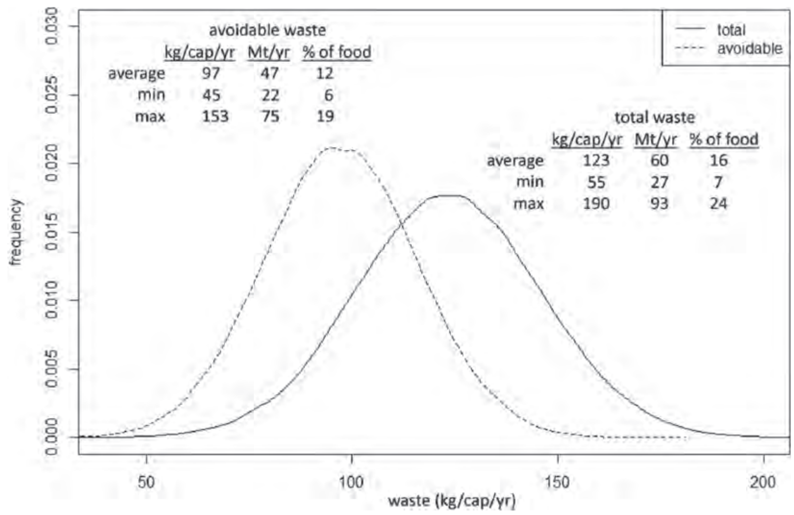

Figure 2. Distribution of total and avoidable EU consumer food waste in kg/cap/yr; statistical values in million tonnes per year (Mt/yr) and % of all food (789 kg/cap/yr or 385 Mt/yr) reaching consumers are also presented.

Table 7. Values (av = average; stdev = standard deviation, max = maximum; min = minimum) per product group of the green and blue $WF_{cons,agr}$ of WASTE_AV.

	$WF_{cons,agr}$ of WASTE_AV (in l/cap/d)							
	Green				Blue			
Product group	av	stdev	max	min	av	stdev	max	min
Cereals	57.603	24.768	97.730	16.850	3.589	1.543	6.090	1.050
Potatoes	8.349	4.110	14.850	1.650	1.518	0.747	2.700	0.300
Sugar	11.880	2.301	15.792	7.901	2.256	0.437	2.998	1.500
Pulses, nuts, oil crops	4.452	1.517	6.650	1.900	0.469	0.160	0.700	0.200
Crop oils	13.587	4.670	20.510	5.860	1.067	0.367	1.610	0.460
Vegetables	10.356	5.154	18.593	1.899	3.085	1.535	5.538	0.566
Fruit	17.131	8.354	31.235	4.646	4.469	2.179	8.148	1.212
Stimulants	24.018	4.621	32.178	16.103	0.149	0.029	0.200	0.100
Spices	0.675	0.128	0.900	0.450	0.075	0.014	0.100	0.050
Alcoholic beverages	4.168	0.987	5.880	2.521	0.298	0.071	0.420	0.180
Meat	105.609	52.666	191.846	25.449	6.945	3.463	12.615	1.673
Animal fats	4.930	1.684	7.210	2.060	0.287	0.098	0.420	0.120
Eggs	3.679	1.170	5.289	1.417	0.216	0.069	0.311	0.083
Milk (excl.butter)	10.557	5.065	28.437	3.840	0.825	0.396	2.222	0.300
Cheese	14.052	7.590	38.590	4.540	1.052	0.568	2.890	0.340
Cream	2.868	1.361	6.978	1.060	0.216	0.103	0.527	0.080
Fish	0	0	0	0	0	0	0	0

occur in manure and animal waste, for which data on purposeful reuse in the food chain were not available [26]. These flows have been included here as a conservative estimate, although it is likely that part of this N will be recovered and not dispersed in the environment.

3.2. Food waste

Figure 2 shows the calculated average amounts of food wasted by EU consumers, which consist of waste at the household and food service/catering sector levels. Total and avoidable waste amounts are given. The figure shows:

- Total waste averages 123 kg/cap/yr or 60 million tonnes (Mt) annually. This represents 16% of all food reaching consumers.
- Avoidable consumer food waste averages 97 kg/cap/yr or 47 Mt/yr. This represents 12% of all food reaching consumers.
- The range between minimum and maximum values of both total and avoidable food waste is very wide.
- Avoidable food waste represents by far the largest part of total food waste; non-avoidable food waste represents only a small fraction.

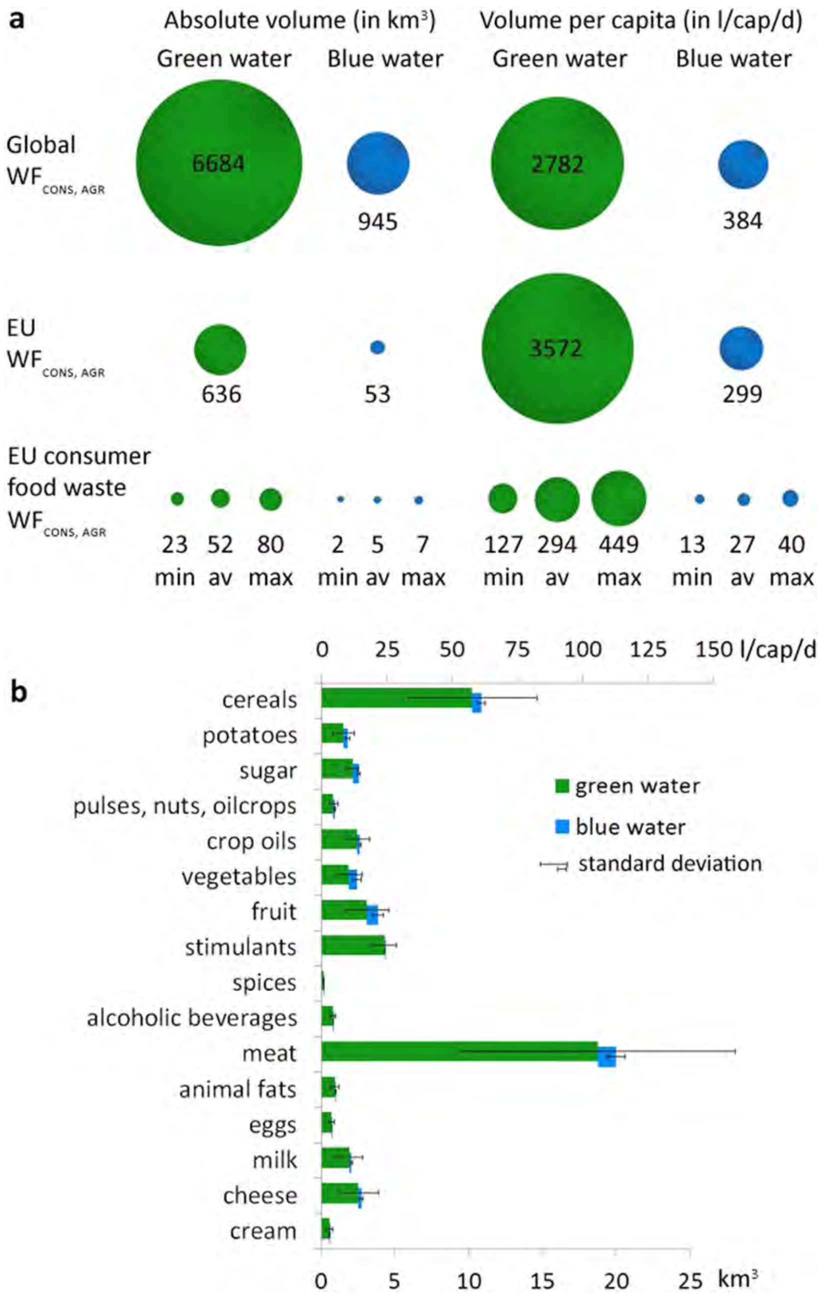

Figure 3. The green and blue $WF_{cons,agr}$ related to EU consumer avoidable food waste for the period 1996–2005: (a) absolute ($km^3\ yr^{-1}$) and per capita volumes (litre per capita per day or l/cap/d) of the global $WF_{cons,agr}$ [16], the total EU $WF_{cons,agr}$ [24] and the $WF_{cons,agr}$ of EU consumer food waste; he areas of the circles are scaled according to the volumes; (b) the average (with indication of the standard deviation) EU consumer food waste green and blue $WF_{cons,agr}$ for different product groups in absolute ($km^3\ yr^{-1}$) and per capita (l/cap/d) volumes.

3.3. WF of avoidable food waste

The $WF_{cons,agr}$ of avoidable food waste amounts from EU consumers are presented in figure 3 and table 7. Values per food product group and the total values are both presented. The total $WF_{cons,agr}$ averages 52 $km^3\ yr^{-1}$ for green water and 5 $km^3\ yr^{-1}$ for blue water, in absolute volumes, or 294 l/cap/d for green water and 27 l/cap/d for blue water. There is a wide range between minimum and maximum $WF_{cons,agr}$ amounts as the range in avoidable food waste amounts is large.

These average absolute volumes represent 8.2% of the EU green $WF_{cons,agr}$ and 8.9% of the EU blue $WF_{cons,agr}$. They also represent 0.8% of the global green $WF_{cons,agr}$ and 0.5% of the global blue $WF_{cons,agr}$.

The product group that accounts for the largest avoidable food waste $WF_{cons,agr}$ is meat (average green 18.8 $km^3\ yr^{-1}$ or 106 l/cap/d and blue 1.2 $km^3\ yr^{-1}$ or 7 l/cap/d), as meat is a very water-intensive product [16, 28].

Other product groups with high amounts of avoidable food waste $WF_{cons,agr}$ are cereals, cheese and crop oils. The blue $WF_{cons,agr}$ of wasted fruit is the second largest after meat, i.e. 0.8 $km^3\ yr^{-1}$ or 4 l/cap/d, as much of the fruit which is either produced in and

Table 8. Values (av = average; stdev = standard deviation, max = maximum; min = minimum) per product group of the NF (N_{cons} and NF_{prod}) of WASTE_AV.

	NF of WASTE_AV (in kg/cap/yr)							
	N_{cons}				NF_{prod}			
Product group	av	stdev	max	min	av	stdev	max	min
Cereals	0.291	0.125	0.493	0.085	0.325	0.140	0.551	0.095
Potatoes	0.051	0.025	0.090	0.010	0.076	0.037	0.135	0.015
Sugar	0.000	0.000	0.000	0.000	0.023	0.004	0.030	0.015
Pulses, nuts, oil crops	0.009	0.003	0.014	0.004	0.005	0.002	0.007	0.002
Crop oils	0.000	0.000	0.000	0.000	0.019	0.006	0.028	0.008
Vegetables	0.044	0.022	0.079	0.008	0.066	0.033	0.119	0.012
Fruit	0.015	0.007	0.027	0.004	0.045	0.022	0.081	0.012
Stimulants	0.007	0.001	0.010	0.005	0.000	0.000	0.000	0.000
Spices	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Alcoholic beverages	0.005	0.001	0.007	0.003	0.060	0.014	0.084	0.036
Meat	0.144	0.072	0.262	0.035	1.550	0.773	2.815	0.373
Animal fats	0.000	0.000	0.000	0.000	0.024	0.008	0.035	0.010
Eggs	0.011	0.003	0.016	0.004	0.032	0.010	0.047	0.013
Milk (excl.butter)	0.027	0.013	0.074	0.010	0.143	0.069	0.385	0.052
Cheese	0.037	0.020	0.102	0.012	0.192	0.104	0.527	0.062
Cream	0.005	0.003	0.013	0.002	0.038	0.018	0.092	0.014
Fish	0.032	0.017	0.062	0.008	0.145	0.079	0.277	0.037

imported into the EU is irrigated [24]. Wasted vegetables and sugar also have a substantial blue $WF_{cons,agr}$ component.

3.4. NF of avoidable food waste

The NF of avoidable food waste amounts from EU consumers is presented in figure 4 and table 8. Both the values per food product group and the total values are presented. The total N_{cons} averages 0.33 Tg N yr^{-1} and the NF_{prod} averages 1.34 Tg N yr^{-1} in absolute quantities or 0.68 kg N/cap/yr and 2.74 kg N/cap/yr in per capita quantities. In addition, the range between minimum and maximum NF amounts is wide as the range in avoidable food waste amounts is large.

These average values represent 11.3% of the N_{cons} supplied to EU consumers and 8.5% of the EU NF_{prod}.

The product group that accounts for the largest avoidable food waste NF is meat (average N_{cons} of 0.07 Tg N yr^{-1} or 0.14 kg N/cap/yr and NF_{prod} of 0.76 Tg N yr^{-1} or 1.55 kg N/cap/yr).

Other product groups with high avoidable food waste NF values are cereals, cheese and milk.

4. Discussion

Our average total food waste estimate of 123 (min 55–max 190) kg/capita annually (kg/cap/yr) for EU consumers is about 20% higher than the estimated 101 kg/cap/yr total food waste (76 kg/cap/yr for households and 25 kg/cap/yr for the food service/catering sector) for the EU-27 by [10]. However, the latter value is well within the range we have defined.

We have estimated that almost 80% (97 (45–153) kg/cap/yr) is avoidable food waste. This average value compares well with the FAO estimate of 95–115 kg/cap/yr of avoidable food waste for Europe [8], although the boundary conditions for our study are quite different to those in the FAO study. The FAO study only used UK avoidable food waste fractions, while our study used food waste fractions from six national studies. The UK presented the highest values among these countries. In our study, we computed consumer food waste from EU citizens in the 28 Member States, while the FAO study analysed the whole of Europe including Russia. In particular, in parts of Eastern Europe outside the EU the average amount of food reaching consumers (FOOD_CONS) is lower compared to that inside the EU.

Our estimated ranges are quite wide because the six national estimates differ substantially, with the highest food waste fractions identified in the UK and the lowest in Romania. Data were gathered for both these studies by means of interviews/the keeping of food diaries. As regards the UK, this diary was complemented with: (1) detailed measurements of the weight and types of food and drink waste acquired from a list of consenting households; and (2) a synthesis of waste data from a list of local authorities. Indeed, household food waste is not easily quantified as it is disposed of either as: (1) municipal waste (solid and organic waste); (2) in the sewer; (3) home composting; or (4) feed for animals. Thus, municipal waste statistics underestimate total household food waste. This restricted the availability of suitable national data for EU Member States.

In addition, the aim of our study was also to differentiate between different product groups. As such, only six national studies qualified. For example, the study in Germany quantifies food waste amounts that

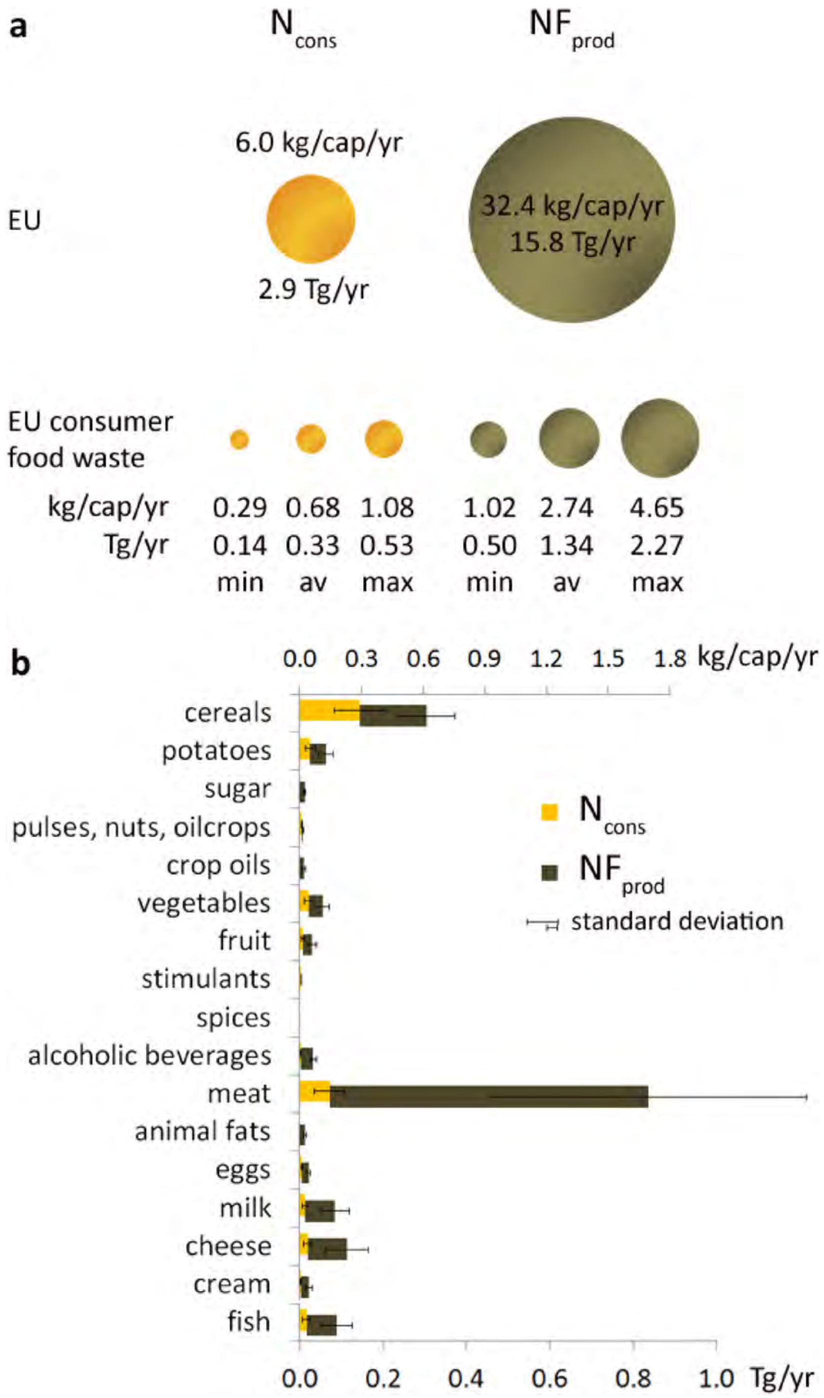

Figure 4. The N_{cons} and NF_{prod} related to EU consumer avoidable food waste for the period 1996–2005: (a) absolute (Tg/yr) and per capita volumes (kg/cap/yr) of the N_{cons} and NF_{prod} for EU food consumption and consumer food waste; the areas of the circles are scaled according to the volumes; (b) the average (with indication of the standard deviation) EU consumer food waste N_{cons} and NF_{prod} for different product groups in per capita (kg/cap/yr) and absolute (Tg/yr) volumes.

are similar to the average amounts in our studies. As shown in table 3, German food waste fractions (CORR2) amounts are average within the CORR2 range and, because of the country's high population weighting, these values are quite dominant.

Nevertheless, even the lowest avoidable waste value within the range (45 kg/cap/yr) is substantial and shows the importance of food waste reduction. EU consumers are responsible for a large proportion of total food loss and waste along the whole food supply chain, a large part of which is avoidable. A minimum of 45 kg/cap/yr equals about 125 g/cap/d—i.e. an average apple a day. A maximum of 153 kg/cap/yr equals about 420 g/cap/d—i.e. a small loaf of bread a day. Within our study, high total as well as avoidable waste amounts are observed for the cereals, fruit and vegetables product groups. A major reason for this is that these food groups have a relatively short shelf-life which means consumers often do not use them in time [29].

A large volume of green and blue water resources are associated with this avoidable waste, although the range in values is also wide. For instance, the average EU green $WF_{cons,agr}$ of EU consumers' wasted food (52 $km^3 yr^{-1}$) roughly equals the total green consumptive water used for crop production in Spain [16]. This means that all green water resources used annually for crop production in Spain—one of the EU's larger agricultural producers—are virtually thrown away by EU consumers through avoidable food waste. The average EU food waste blue $WF_{cons,agr}$ (5 $km^3 yr^{-1}$) is slightly higher than the total EU blue consumptive municipal water use (4 $km^3 yr^{-1}$ or 23 l/cap/d) [24] or equals 1.5 times the annual flow of Italy's River Arno [48].

In addition, high NF values are related to these avoidable waste amounts, once again within a substantial range. The N contained in avoidable food waste averages 0.68 kg/cap/yr or almost 2 g/cap/d. The mean N footprint (any remaining N that was used in the food production process) is roughly 1.34 Tg yr^{-1}, which is equivalent to mineral fertiliser use in the UK and Germany combined [49].

Although the highest total and avoidable waste amounts are observed for the cereals, fruit and vegetables product groups, it is wasted meat that accounts for the highest related wasted water and nitrogen resources. For instance, the green $WF_{cons,agr}$ of wasted meat is slightly higher than the total green consumptive water use for crop production in the UK (18.0 $km^3 yr^{-1}$) [16]. The blue $WF_{cons,agr}$ of wasted meat is roughly equal to the total blue consumptive municipal water use in Germany (0.6 $km^3 yr^{-1}$) and France (0.6 $km^3 yr^{-1}$) combined. This is because the production of livestock products, especially meat, is very resource intensive. It has already been observed by [9, 28, 50] that a reduction in meat intake in the average consumer's diet has the largest associated reduction effect on a consumer's WF_{cons}. This is important as it can show EU consumers that they can save a lot of resources by reducing their avoidable meat waste.

5. Concluding remarks

In our study, we have calculated both the total and avoidable food waste of EU consumers. We have also differentiated between different food product groups. Uncertainty is very high in these waste quantities, but has never been assessed in previous studies. Thus, for the first time, we have provided an estimate of the possible range, based upon statistical data from six EU Member States. Data from other Member States were either not suitable or did not exist. Our findings show that:

- Total consumer food waste averages 123 kg/cap/yr, i.e. 16% of all food reaching consumers.
- Avoidable consumer food waste averages 97 kg/cap/yr, i.e. 12% of all food reaching consumers.
- Avoidable food waste represents by far the largest part of total food waste.
- Particular product groups are proportionally wasted more than others, especially vegetables, fruit and cereals. A major reason for this is that they have a relatively short shelf-life which means consumers often do not use them in time. Another reason is the fact that they are generally cheaper per weight unit as compared to other product groups like meat. Therefore consumers often tend to over-purchase the former.
- There is a very wide range between minimum and maximum amounts of both total (from 55 to 190 kg/cap/yr) and avoidable (from 45 to 153 kg/cap/yr) food waste. This is due to the fact that lifestyles and purchasing power can differ substantially between Member States.
- Even the lowest amount of avoidable food waste (45 kg/cap/yr) represents a substantial quantity. It is roughly equal to the weight of an apple a day or, for all the citizens in the EU together, 22 million tonnes of food each year. A maximum of 153 kg/cap/yr is equal to about 420 g/cap/d (i.e. a small loaf of bread a day) or for all the citizens in the EU together, 75 million tonnes of food each year. Consequently, reducing food waste should be a concern for every consumer.

We have calculated water and nitrogen resources associated with avoidable food waste. To quantify the water resources related to these amounts of wasted food we have used the WF of consumption (WF_{cons}) concept. In particular, we have assessed the green and blue WF_{cons} of agricultural products ($WF_{cons,agr}$) for food wasted. To quantify the nitrogen resources related to these wasted amounts of food we have used the NF concept. In particular, we have assessed the nitrogen contained in food (N_{cons}) and the food production NF (NF_{prod}) for avoidable food waste. We have determined that:

- The average $WF_{cons,agr}$ of avoidable food waste from EU consumers amounts to 52 $km^3 yr^{-1}$ green water and 5 $km^3 yr^{-1}$ blue water in absolute volumes or 294 l/cap/d green water and 27 l/cap/d blue water.
- The average N_{cons} of avoidable food waste from EU consumers amounts to 0.33 Tg N yr^{-1} and the NF_{prod} to 1.34 Tg N yr^{-1} in absolute quantities or 0.68 kg N/cap/yr and 2.74 kg N/cap/yr in per capita quantities.
- The range between minimum and maximum values of the $WF_{cons, agr}$ and NF related to avoidable

food waste is very wide because the range in food waste values is large.

- Among all the product groups, meat accounts for the largest avoidable food waste footprints ($WF_{cons, agr}$ and NF), although wasted amounts are much smaller when compared to other food product groups. That is because meat production is very resource intensive. In other words, a small reduction in wasted meat already equates to a large reduction in wasted water and nitrogen resources. A similar observation was made by Cuellar and Webber [14] for energy. The authors state that wasted meat in the USA is responsible for the most wasted energy, despite a smaller relative fraction of meat being wasted compared with grains.
- This is also true for other livestock products such as milk and cheese, although to a lesser extent.
- On the other hand, wasted resources associated with fruit and vegetables are relatively low compared to other food product groups, although the wasted quantities from these product groups are high.

Theoretically, zero avoidable food waste is a possibility for EU consumers. This would not only save a lot of money for the consumers themselves, but also for local authorities which have to pay for food-waste collection and treatment. In addition, this would not only save a large volume of water and avoid losses of reactive nitrogen, but it would also preserve other natural resources such as phosphorus, land and energy. In a world with limited resources, food security can only be achieved by a more sustainable use of resources along with adaptations to our consumption behaviour, including the reduction or, ideally, the eradication of food waste [6, 7, 46].

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