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Lost food, wasted resources: Global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use

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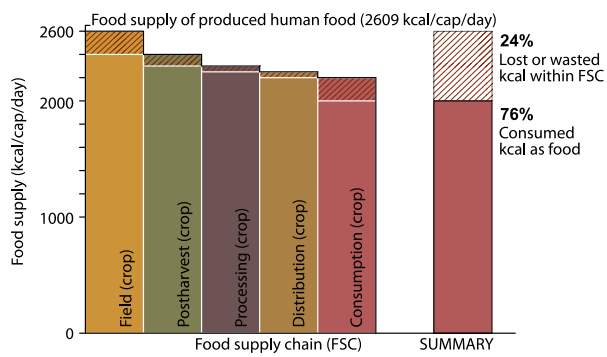
HIGHLIGHTS

- ► Losses of food supply and related resources were studied at a global scale.
- ► Around 1/4 of the produced food (in terms of kcal) is lost in the food supply chain.
- ► 23–24% of total use of water, cropland and fertilisers are used to produce losses.
- ► Around half of the losses could be prevented with a more efficient supply chain.
- ► One billion extra people could be fed if food crop losses could be halved.

GRAPHICAL ABSTRACT



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ABSTRACT

Reducing food losses and waste is considered to be one of the most promising measures to improve food security in the coming decades. Food losses also affect our use of resources, such as freshwater, cropland, and fertilisers. In this paper we estimate the global food supply losses due to lost and wasted food crops, and the resources used to produce them. We also quantify the potential food supply and resource savings that could be made by reducing food losses and waste. We used publically available global databases to conduct the study at the country level.

We found that around one quarter of the produced food supply (614 kcal/cap/day) is lost within the food supply chain (FSC). The production of these lost and wasted food crops accounts for 24% of total freshwater resources used in food crop production (27 m^3/cap/yr), 23% of total global cropland area (31×10^{-3} ha/cap/yr), and 23% of total global fertiliser use (4.3 kg/cap/yr). The per capita use of resources for food losses is largest in North Africa & West-Central Asia (freshwater and cropland) and North America & Oceania (fertilisers). The smallest per capita use of resources for food losses is found in Sub-Saharan Africa (freshwater and fertilisers) and in Industrialised Asia (cropland). Relative to total food production, the smallest food supply and resource losses occur in South & Southeast Asia.

If the lowest loss and waste percentages achieved in any region in each step of the FSC could be reached globally, food supply losses could be halved. By doing this, there would be enough food for approximately one billion extra people. Reducing the food losses and waste would thus be an important step towards increased food security, and would also increase the efficiency of resource use in food production.

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1. Introduction

The world continues to face a challenge to feed its people sustainably (FAO, 2009; Pelletier and Tyedmers, 2010; Tilman et al., 2001); globally around one billion people are malnourished (e.g. Naylor, 2011). In the future, food production will also be affected by both projected increases in population in many regions (UN, 2011) and climate change (Nelson et al., 2010; Schmidhuber and Tubiello, 2007). Therefore, the challenge to feed the world's population will become even larger. Food security has been high on the political agenda during recent years, due to factors such as volatile food prices, the use of food crops as biofuel or fodder, and droughts (e.g. Donner, 2007; Godfray et al., 2010; Naylor, 2011; Naylor and Falcon, 2010; Rosegrant et al., 2009). Several measures have been suggested to meet the increasing challenges of feeding the world's population and increasing food security in a sustainable way, such as: halting farmland expansion, in particular in the tropics; closing 'yield gaps' on underperforming land; increasing cropping efficiency; shifting diets; and reducing waste (Foley et al., 2011; Godfray et al., 2010). By applying these measures together, food production could be doubled with our available resources without increasing environmental impacts (Foley et al., 2011). In this study we concentrate on the last of those measures, i.e. reducing waste, since about one third of the food produced globally (in terms of weight) is lost or wasted (Gustavsson et al., 2011), and reducing this would thus be an important measure to increase global food supply.

Food losses and waste also impact on other natural resources, many of which are scarce. Three key related resources are freshwater, cropland, and fertilisers. Water is scarce in many regions (Alcamo et al., 2003; Kummu et al., 2010; Oki and Kanae, 2006; Vörösmarty et al., 2000; Wada et al., 2011) and water scarcity is one of the most pressing challenges faced by human populations (Rockström et al., 2009). The agricultural sector is responsible for 70% of global freshwater withdrawals and 90% of consumptive water uses (Döll, 2009; Shiklomanov, 2000). Cropland currently occupies about 1.53 billion hectares, or 12% of the Earth's ice free land (Foley et al., 2011), and the areas most suitable for cropping have already been converted to cropland (Ramankutty et al., 2002). Expansion is therefore often into marginal areas and is associated with environmental degradation (Friedlingstein et al., 2010; West et al., 2010). Food production is also strongly associated with the use of synthetic fertilisers, which contain finite natural resources such as phosphorous (Dawson and Hilton, 2011). Moreover, the use of synthetic fertilisers has negative impacts on biodiversity and water quality (Bobbink et al., 2010; Galloway et al., 2008; Gruber and Galloway, 2008; Smil, 2002).

Although the importance of natural resources used to produce lost and wasted food products has been increasingly highlighted (e.g. Gustavsson et al., 2011; Lundqvist, 2010; Lundqvist et al., 2008), detailed analyses of the magnitude of the problem and the corresponding spatial patterns are not yet available, to the best of our knowledge. However, such analyses are now possible based on the results of recent studies on global food losses and food waste (Gustavsson et al., 2011), water footprints of agricultural products (Mekonnen and Hoekstra, 2011), and FAOSTAT databases (FAO, 2011b). Moreover, although the lost and wasted food products have been quantified in terms of weight, no detailed global estimates exist in terms of lost nutritional energy (kcal). Given that there are already a billion malnourished people, and pressure on limited natural resources is growing, it is extremely important to understand how many kilocalories are actually lost within the food supply chain (FSC) and how many of these kilocalories and resources could be preserved if FSC losses were reduced. Hence, our main objectives are: i) to provide the first spatial global scale analysis of reduction in food supply (in terms of kilocalories) due to lost and wasted food crops intended to human food; ii) to quantify the resource use of freshwater, cropland, and fertilisers in producing food crops that are lost and wasted; and iii) to quantify the potential savings of food supply and related resources that could be made by reducing food losses and waste.

2. Definitions and materials

2.1. Definitions

In this study, we refer to total losses and waste within the different steps of the FSC (production, postharvest, processing, distribution, and consumption) as FSC losses. We further differentiate these FSC losses between 'food losses' and 'food waste'. We refer to food losses as those in the production, postharvest, and processing of products, and food waste as losses during distribution and consumption, in line with other studies (Gustavsson et al., 2011; Parfitt et al., 2010). Brief explanations of the definitions for each category of FSC losses are provided in Table 1.

In our loss and waste analysis, we only included the food crop products intended directly for human food consumption (see the list of the included products in Table S1 in the Online Supplement). Products directed to animal feed, seed, and other uses (e.g. industry, biofuels) were thus excluded from our analysis. We refer to the total production of analysed food crop products (including human food, feed, seed, and other use) as 'total production', and the part intended directly for human food as 'total food production'. The domestic food supply quantity (DFSQ; see Fig. 1 and Section 3.3) refers to the amount of food crops available to be used in a spatial unit in question after production and postharvest losses, imports, exports, and stock variation have been considered.

We also estimated the direct use of several resources in the production of those FSC losses, namely freshwater (more specifically blue water; referring to water in aquifers and water courses (Falkenmark, 1997)), cropland, and mineral fertilisers (N, P_2O_5 and K_2O). However, we did not include second order effects caused by the interplay of the different resources (e.g. green water use; referring to rainwater that is evaporated from water stored in soil (Falkenmark, 1997), the impact of fertiliser use on water quality, and the relation between fertiliser use and cropland area). Moreover, since our focus is on quantifying the lost food supply and related resources, we did not consider the potential waste reductions that could be gained through technological innovations and political and economic measures.

2.2. Global agricultural production

National scale crop production was derived from the FAO Food Balance Sheets (FAO, 2011d). Due to year-to-year variations in food production, we averaged the data over the years 2005–2007 (the three most recent years for which the data are available). We included only food crops (i.e. vegetal products) in our study due to the lack of global spatial data to define in detail how the products directed to feed are used by different animal groups. The food crops considered in this study account for 83% of total food supply (2761 kcal/cap/day; averaged over years 2005–2007) whilst animal products account for the remaining 17% (FAO, 2011d).

The database includes 44 main food crop products (Table S1 of the Online Supplements), and we divided it into four commodity-groups (after Gustavsson et al., 2011), namely: i) cereals, ii) fruits & vegetables, iii) oilseeds & pulses, and iv) roots & tubers. Matter flows of each product after the postharvest step were divided into locally produced quantity, stock variation, import, and export (Fig. 1A) according to FAO Food Balance Sheets (FAO, 2011d). From these, we calculated the DSFQ, which was further subdivided into three classes indicating how the products are used: fresh food, processed food, and waste (called here postharvest losses).

Table 1
Brief explanations of definitions of food losses and waste (see more details in Gustavsson et al., 2011), computation of different FSC losses (see also Fig. 1, and Online Supplementary), and the examples of possible interventions to avoid losses (see more in e.g. Gustavsson et al., 2011; Parfitt and Barthel, 2011; Parfitt et al., 2010; Stuart, 2009). The loss and waste percentages are based on Gustavsson et al. (2011; pages 26–27) whilst all the FSC data are based on FAO Food Balance Sheets (FAO, 2011d). AFR stands for Sub-Saharan Africa, EUR for Europe (including Russia), INA for Industrialised Asia, LAM for Latin America, NAWCA for North Africa & West-Central Asia, NAO for North America & Oceania, and SSEA for South & Southeast Asia. DFSQ stands for domestic food supply quantity.

Loss name	Definition	How computed	Possible interventions to avoid losses
Agricultural losses	Contains losses due to mechanical damage and/or spillage during harvest operation, crop sorting etc. Percentage varies from 2% for cereals in industrialised regions (EUR, NAO, INA) to 20% for roots & tubers (EUR, NAO, INA) and fruits & vegetable (EUR, NAO, LAM).	Calculated from the local production (FSC step (1) in Fig. 1A), derived from Food Balance Sheets (FAO, 2011d).	*In industrialised countries*: cooperation among farmers could reduce risk of overproduction that often leads to agricultural losses (Stuart, 2009). *In developing countries*: better organised small farmers, technology transfer, education (Gustavsson et al., 2011).
Postharvest losses	Contains losses due to storage and transportation between farm and distribution, and spillage and degradation during handling. Percentage varies from 0% for oilseeds & pulses in NAO to 19% for roots & tubers in SSEA.	Calculated from the harvested production (step 2 in Fig. 1A), i.e. the local production reported in Food Balance Sheets (FAO, 2011d).	*In industrialised countries*: Improved on-farm facilities. *In developing countries*: more reliable transportation network, energy and market systems; enhanced infrastructure during transportation and storage (Rolle, 2006; Stuart, 2009).
Processing losses	Includes losses during industrial or domestic processing. Percentage varies from 0.5% for cereal products in industrialised regions to 25% for fruits & vegetables in AFR and SSEA.	Calculated from the part of DFSQ that was processed (based on FAO, 2011d) before distribution and consumption (step 7 in Fig. 1A).	*In industrialised countries*: develop market for 'sub-standard' products that are eatable, enhanced production lines (Stuart, 2009). *In developing countries*: capacity building, more investments on food processing (Gustavsson et al., 2011).
Distribution waste	Includes losses and waste in the market system, including wholesale markets, supermarkets, retailers, and wet markets. Percentage varies from 1% for oilseeds & pulses in industrialised regions to 17% for fruits & vegetables in AFR.	Calculated from the total amount of processed and fresh food (step 8 in Fig. 1A) derived from DFSQ. For the processed fruits & vegetables and roots & tubers the waste percentages were 59% of the ones for the fresh food.	*In industrialised countries*: lower standards for size, weight, etc. (Gustavsson et al., 2011). *In developing countries*: marketing cooperatives and improved marketing facilities (Gustavsson et al., 2011).
Consumption waste	Includes all the losses and waste at the household level. Percentage varies from 1% for cereals in AFR and oilseeds & pulses in SSEA to 30% for roots & tubers in NAO.	Calculated from the total amount of consumed food (step 9 in Fig. 1A). For the processed fruits & vegetables and roots & tubers the waste percentages were 20% of the ones for the fresh food.	*In industrialised countries*: public awareness, smaller packages, better planning in restaurants and households (Gustavsson et al., 2011). *In developing countries*: not a big problems as consumption waste is already very low.

2.3. FSC losses

We estimated the food loss and waste for each step of the FSC (Fig. 1A). Since there are few first-hand data available on actual FSC losses (except for a few countries, e.g. Parfitt et al., 2010), we used the commodity-group (see Section 2.2) specific loss percentages provided by Gustavsson et al. (2011; pages 26–27) per region for each country belonging to that region. It should be noted that Gustavsson et al. (2011) had to estimate loss and waste percentages in regions where first hand data are not available, in order to fill gaps in the first hand data. Our results are therefore subject to the assumptions underlying those estimates.

2.4. Water, cropland, and fertilisers resources

We derived the volumes of water required to produce the analysed food crops from a database of blue water footprints by country (Mekonnen and Hoekstra, 2011). Fertiliser consumption (sum of N, P_2O_5 and K_2O) and crop specific harvested area were derived at the national level (averaged over 2005–2007) from the FAOSTAT ResourceSTAT database (FAO, 2011f). For the countries where no fertiliser data are available (1.5% of the total crop harvested area), we used the average regional fertiliser use on cropland (t/ha).

2.5. Population and available freshwater resources

We extracted renewable freshwater resources at the national scale from the AQUASTAT database (FAO, 2011a); these are required for the comparison to water use for FSC losses. For national population data, we used the FAOSTAT Population module database averaged over years 2005–2007 (FAO, 2011e), based on the 2010 Revision from the UN Population Division (UN, 2011).

3. Methods

Our analysis involved three main steps: firstly the calculation of FSC losses in terms of weight (kg) and food supply (kcal) (Fig. 1A); secondly the calculation of the resources used to produce these losses (Fig. 1B–D); and thirdly the scenario estimates of the potential savings of food supply and related resources that could be made through a more efficient FSC. At the country level, we estimated the FSC losses in each FSC step for each analysed product, and linked the corresponding resource use to it. The methodology is presented in more detail in the following subsections.

Methodologically, our study expands the pioneering study on global food loss and food waste by Gustavsson et al. (2011) in following ways: i) our analysis was carried out at the country level whilst Gustavsson et al. (2011) carried out their analysis at a regional level; and ii) we included food supply (in terms of kcal) to quantify resource (water, land, fertilisers) use for FSC losses in our study whilst Gustavsson et al. (2011) only analysed losses in terms of weight. A more detailed comparison of these two studies is provided in the Discussion section.

3.1. FSC losses calculation

We calculated the food supply potential of the total production (i.e. including the feed, seed, and other use) and the resources used to produce the total production, but included in our loss and waste analysis only the fraction of the total production directed to human food (i.e. total food production; Fig. 1). There are five loss categories within the FSC: i) agricultural losses; ii) postharvest losses; iii) processing losses; iv) distribution waste; and v) consumption waste (Fig. 1A, Table 1; see also example calculation in Figure S2 of the Online Supplement). For each FSC step, we used the regional loss percentage defined by Gustavsson et al. (2011), except for postharvest

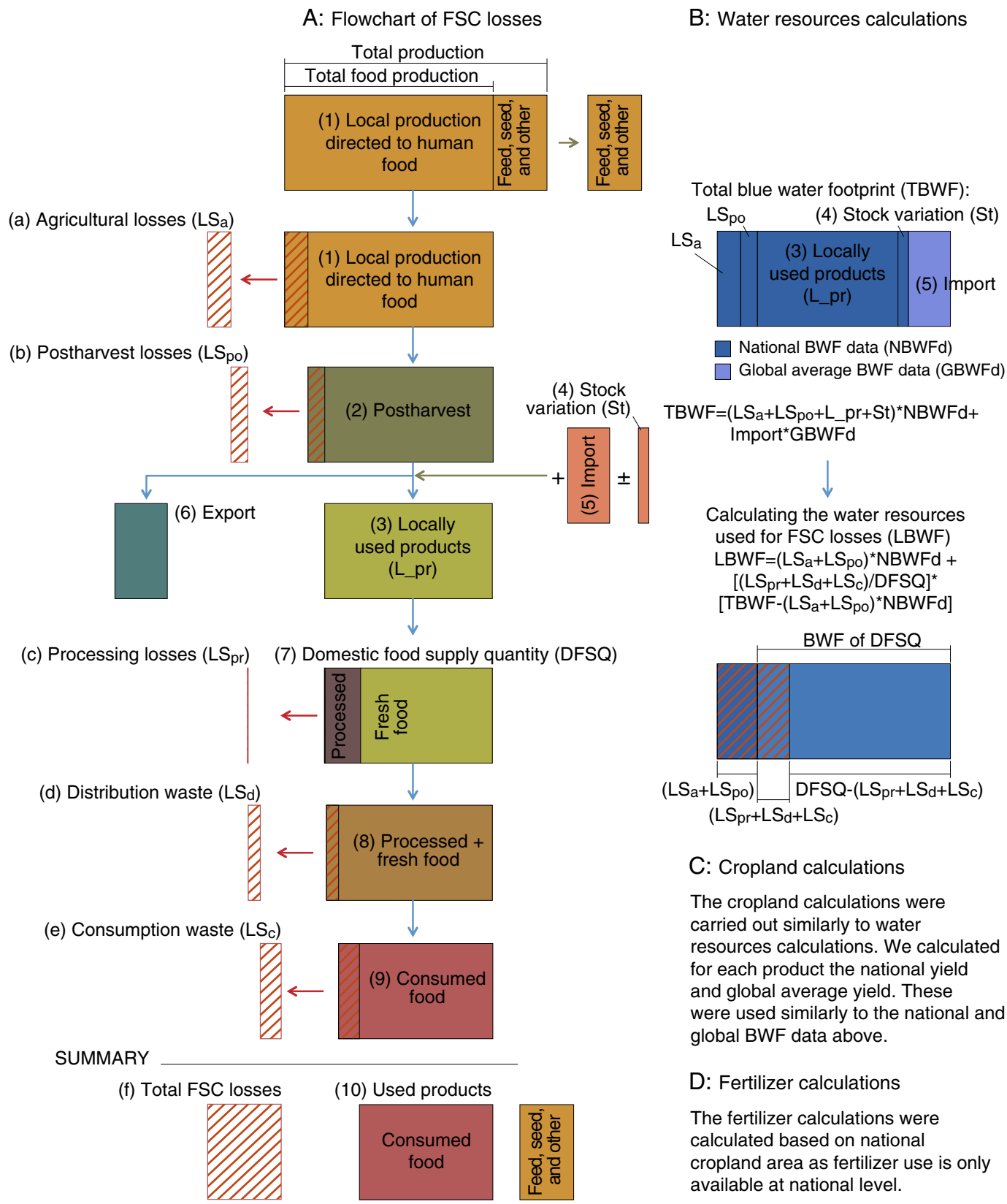

Fig. 1. Flowcharts of the calculations. A: Schematic flowchart of the FSC (food supply chain) and FSC losses within it. Only the fraction of the total production directed to human food (i.e. total food production) was included into the calculations (animal feed, seed, and other use were excluded); B: flow chart for calculations of consumed water resources and use of water resources for FSC losses (BWF stands for blue water footprint); C: short explanation of cropland calculations; D: short explanation of fertiliser calculations.

loss in cases when there are data available in the FAO Food Balance Sheets (FAO, 2011d).

FAO Food Balance Sheets do not differentiate the fraction intended for direct human consumption from the total production. These data are, however, available for the DFSQ (i.e. after imports, exports, and stock variation; see Fig. 1). Therefore, we used the fraction given for DFSQ in the FAO Food Balance Sheets (2011d) to calculate the part of total production intended for direct human consumption. In most countries this assumption is rather realistic, but in countries where the fraction of other uses (e.g. feed and seed) is larger for exported food than for locally consumed food, this assumption may overestimate the actual calculated agricultural and postharvest losses; and vice versa.

We took into account the stock variation (i.e. changes in government and private sector stocks) (Fig. 1A) based on data in the FAO Food Balance Sheets (FAO, 2011d). For imported and exported food products, we included agriculture and postharvest losses in the national losses of the country in which the food was produced. This results in larger per capita losses for net food exporters (such as Australia, Brazil, and the United States) compared to net food importers (such as many countries of the North Africa & West-Central Asia region).

Processing losses were calculated only for the products that are further processed (i.e. not used fresh), as stated in FAO (2011d). The distribution waste and consumption waste are considerably lower for processed fruits & vegetables and roots & tubers compared to fresh products (J. Gustavsson, personal communication, March 2012), due to longer preservation times. The waste percentages for processed products are 0.59 times those of the fresh food for distribution waste, and only 0.2 times those of fresh food for consumption waste (modified from Gustavsson et al., 2011; see their Annex 5 where the waste percentages for the processed food are given for South & Southeast Asia. We used their given ratio for all the regions as more detail data are not available).

3.2. Food supply calculations

After estimating FSC losses in terms of weight, these were converted to losses in food supply (kcal) by using product and country specific conversion factors. We calculated these conversion factors based on the FAO Food Balance Sheets (FAO, 2011d), which provide country specific data for each analysed product both in kg and in kcal. Average food supply values over the period 2005–2007 were used in the calculations. In cases where national conversion data are not available, we used product specific global averages. Altogether, only 3.3% of the global food supply was calculated with global average values.

3.3. Freshwater calculations

After calculating food supply, we computed the blue water footprint for the total DFSQ (domestic food supply quantity, i.e. fresh and processed food used domestically after the imports and exports) and the losses that occurred before that step by summing up the agricultural and postharvest losses (a and b; Fig. 1A), locally used products (3; Fig. 1A), stock variation (4; Fig. 1A), and import (5; Fig. 1A). Then we removed exported products from this sum (6; Fig. 1A), resulting in the country's total blue water footprint (TBWF; Fig. 1B) of the agricultural product in question.

For the imported part (5; Fig. 1A) of the DFSQ (7; Fig. 1A) of each product, we used the weighted average water footprint of all exporting countries (Fig. 1B), whilst we used the national water footprint for other parts of the DFSQ. Where national data are not available for a particular product in a given country, we used the global average data. Altogether, 8.6% of the total global water footprint was calculated with this average data.

To calculate the equivalent volume of the blue water footprint that was used to produce the FSC losses, we first calculated the water footprint of agricultural (LS_a) and postharvest (LS_{po}) losses by using the national water footprint data. For processing losses and distribution and consumption waste, we used their proportion of the DFSQ (Fig. 1B). All the calculations were carried out separately for each product in each nation.

3.4. Cropland and fertiliser use calculations

Cropland calculations were carried out in a similar manner to the freshwater calculations. We used country scale crop yield data from FAO (2011c) for the nationally produced products. For the imported products we used the weighted average yield of all exporting countries. For the agricultural and postharvest losses we used national yields to estimate the equivalent cropland area. Then, we calculated the total cropland area needed for the DFSQ and the equivalent cropland for the processing losses and distribution and consumption waste of the commodity in question.

Crop specific fertiliser use data are available for several countries from FAO (FAO, 2012) or IFA (International Fertiliser Association) (IFA, 2012), but the reference year in these databases differs between (and even within) countries. Additionally, fertiliser use is often only estimated for a few main crops. Applying those crop specific fertiliser use rates would therefore result in an underestimate of fertiliser use for crops with minor extent, such as vegetables. Therefore, we used national fertiliser use data based on FAO ResourceSTAT (FAO, 2011f), and assumed that fertilisers are equally distributed over the entire harvested cropland in a country. Consequently, the country-wise fraction of fertiliser losses is similar to the fraction of cropland losses.

3.5. Minimum loss scenario

Finally, we developed a scenario to estimate how the use of resources on FSC losses could potentially be reduced (the minimum loss scenario) compared to the current situation. This scenario assumes that for each step of the FSC, the lowest loss and waste percentages achieved in any of the regions are also achieved in all other regions (Table S2 of the Online Supplements). For example, the lowest consumption waste percentage for cereals is achieved in Sub-Saharan Africa (1%); this percentage was then applied for postharvest losses in all of the other regions. Our scenario analysis focuses on the potential for reduction in food losses and food waste and leaves a discussion of the associated economic, social, and cultural issues to future work.

4. Results

4.1. Food supply losses and waste

According to our analyses, the total production of food crops provides on average 3938 kcal/cap/day (Fig. 2A). Globally, around half of the total food supply is consumed by humans, over one quarter is directed to animal feed, 16% is lost or wasted within the FSC, and in total 6% is directed to seed or other use (Fig. 2A; Table S3 in the Online Supplement). There are, however, large regional differences, as the share of total production directed to uses other than human food ranges from 16% in South & Southeast Asia to 54% in North America & Oceania and Europe (Table S3).

Approximately 43% of the kilocalories directed globally from crop production to animal feed are returned to human use as food products (FAO, 2011d). Therefore, at a global scale the livestock sector is a net drain on food supply, with approximately 600 kcal/cap/day being lost. However, this part of the food supply chain and its corresponding loss of efficiency are outside the scope of this paper, and are therefore not analysed in more detail.

Total food production of the analysed crop commodities is 2609 kcal/cap/day, of which approximately 1995 kcal/cap/day (76%) is actually used by humans, and 614 kcal/cap/day (24%) is lost or wasted within the FSC (Fig. 2A; Table S3). The largest per capita food

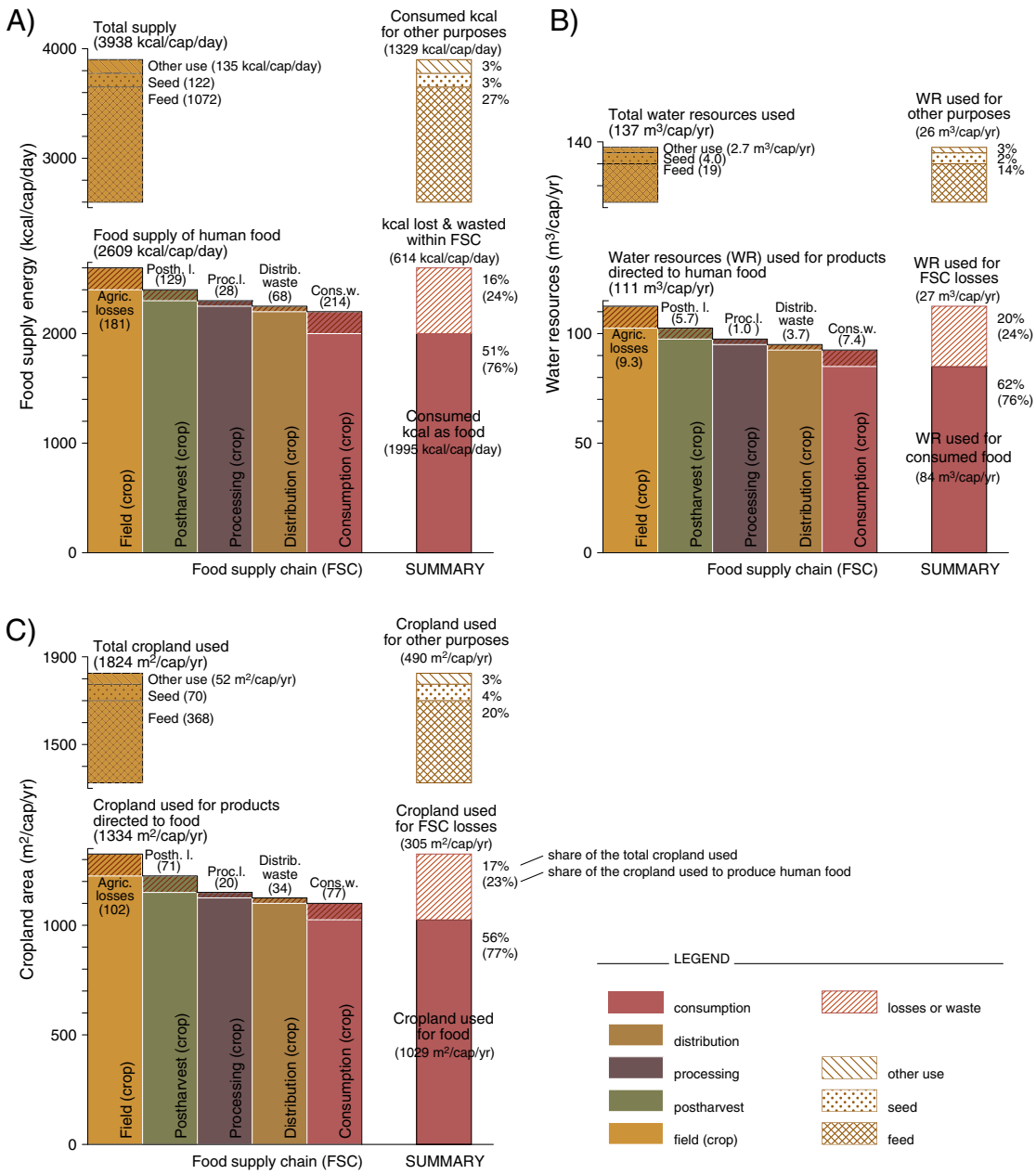

Fig. 2. Division of the produced and lost food supply, and resources used for production and FSC (food supply chain) losses averaged over the years 2005–2007; A: food supply (kcal/cap/day); B: water resources (WR; m^3/cap/yr); and C: cropland (m^2/cap/yr). The production is divided into two parts: the fraction directed to human food and the fraction directed to other purposes (animal feed, seed, and other use). The losses and waste are calculated in our analyses only for the fraction directed to human food. The percentages in brackets are associated with the share of the item in question of the production directed to human food. Note: totals may not sum up due to rounding; this analysis was not conducted for fertilisers due to data limitations (See Section 3.4). See tabulated data in Table S3 of the Online Supplement.

supply losses occur in North America & Oceania (1334 kcal/cap/day), where the produced food supply is by far the largest (Table 2). The lowest per capita losses occur in South & Southeast Asia (404 kcal/cap/day) (Table 2). Likewise, FSC losses relative to total food production are largest in North America & Oceania (32%) and lowest in South & Southeast Asia (18%). A country level overview of per capita food supply losses is given in Fig. 3A.

When examining the regional FSC losses in different FSC steps (Fig. 4A), the globe can be divided into two parts: a) middle/high-income countries, where over half of the food supply losses occur in distribution and consumption; and b) low-income countries, where the main losses occur during agricultural and postharvest steps. When examining the losses in different FSC steps globally, agriculture losses and consumption waste each account for around 30% of the total losses, whilst postharvest losses account for one fifth (Fig. 4B). In absolute terms, the largest FSC losses are found in Industrialised Asia and South & Southeast Asia (Fig. 4B), mainly due to the large population in these regions (Table 2).

Cereals account for over half (57%) of the total FSC losses (Fig. 5A). This could be expected, as they provide 63% of the total food supply (after losses and waste) of the analysed food crops. On the other hand, only 22% of total produced cereals are lost, compared to 39% of fruits & vegetables and 33% of roots & tubers. We found only moderate differences between regions; the only notable difference is that

Table 2
Population, food production, food supply losses (l&w), total use of resources for food crop production, and use of resources for FSC losses (use for l&w) per region. Included resources are freshwater, cropland, and fertilisers (sum of N, P_2O_5, and K_2O). All the results are averaged over the years 2005–2007. DFSQ stands for the domestic food supply quantity. AFR stands for Sub-Saharan Africa, EUR for Europe (including Russia), INA for Industrialised Asia, LAM for Latin America, NAWCA for North Africa & West-Central Asia, NAO for North America & Oceania, and SSEA for South & Southeast Asia. Note: some countries are missing from the analyses due to data constraints (see Figure S1 in the Online Supplements for missing countries, regional delineation, and region abbreviations); totals may not sum up due to rounding.
Source for population data: FAOSTAT (FAO, 2011b).

Region	Popul. ($\times 10^6$)	Food supply		Water resources		Cropland		Fertilisers (nutr.)	
		Production	l&w	Total use	Use for l&w	Total use	Use for l&w	Total use	Use for l&w
		[kcal/cap/day]	[kcal/cap/day]	[m^3/cap/yr]	[m^3/cap/yr]	[m^2/cap/yr]	[m^2/cap/yr]	[kg/cap/yr]	[kg/cap/yr]
AFR	766	2404	506 (21%)	52	12 (22%)	1950	431 (22%)	3.6	0.7 (20%)
EUR	749	2511	720 (29%)	59	18 (31%)	1282	334 (26%)	15.8	3.9 (25%)
INA	1518	2729	678 (25%)	74	19 (25%)	948	232 (25%)	27.8	6.8 (25%)
LAM	559	2720	693 (25%)	65	22 (34%)	1475	361 (24%)	20.8	5.2 (25%)
NAWCA	378	2936	775 (26%)	258	86 (33%)	1473	407 (28%)	15.9	4.2 (27%)
NAO	357	4230	1334 (32%)	120	42 (35%)	1611	498 (31%)	30.5	9.3 (30%)
SSEA	2168	2279	404 (18%)	161	30 (18%)	1298	237 (18%)	15.5	2.8 (18%)
Global	**6495**	**2609**	**614 (24%)**	**111**	**27 (24%)**	**1334**	**305 (23%)**	**18.3**	**4.3 (23%)**

roots & tubers related losses have a relatively large share of total FSC losses in Sub-Saharan Africa compared to other regions (Fig. 5A).

4.2. Use of freshwater resources for the FSC losses

Altogether, 62% of the irrigation water used to produce the commodities considered in this study is for crop products consumed directly as food, whilst 20% of the water is used for FSC losses and 14% for feed (Fig. 2B; Table S3). Seed and other uses only account for 5% of the total use. There are regional differences, but these are not as large as in the case of food supply (Table S3). Feed accounts for over 20% of total water use in three regions (Europe, North Africa & West-Central Asia, and North America & Oceania), whilst in Africa and South & Southeast Asia it only accounts for 4–7%.

The total freshwater volume used to produce the analysed food products directed to human food is 723 km^3/yr, i.e. 111 m^3/cap/yr (Table 2). Of this volume, approximately 84 m^3/cap/yr (76%) is used for human food and 27 m^3/cap/yr (24%) for FSC losses (Fig. 2B). The largest per capita use of water resources for FSC losses is in the North Africa & West-Central Asia region (86 m^3/cap/yr), and the lowest is in Sub-Saharan Africa, Industrialised Asia, and Europe (12–19 m^3/cap/yr) (Table 2). The largest losses relative to total water use are in Latin America (34%) and North America & Oceania (35%), and the smallest are in South & Southeast Asia (18%). A country level overview is given in Fig. 3B.

As is the case for food supply, the world can be divided into two groups when the freshwater use for FSC losses is examined by FSC steps (Fig. 4C). Globally, agriculture, postharvest, and consumption each account for around one quarter of the total water resources used for FSC losses (Fig. 4C). In absolute terms, the largest values are found in South & Southeast Asia (Fig. 4D), due to the region's large population and relatively high water use per capita (Table 2).

Cereals and fruits & vegetables together account for three quarters of the total water use for FSC losses (Fig. 5B). This could be expected, as

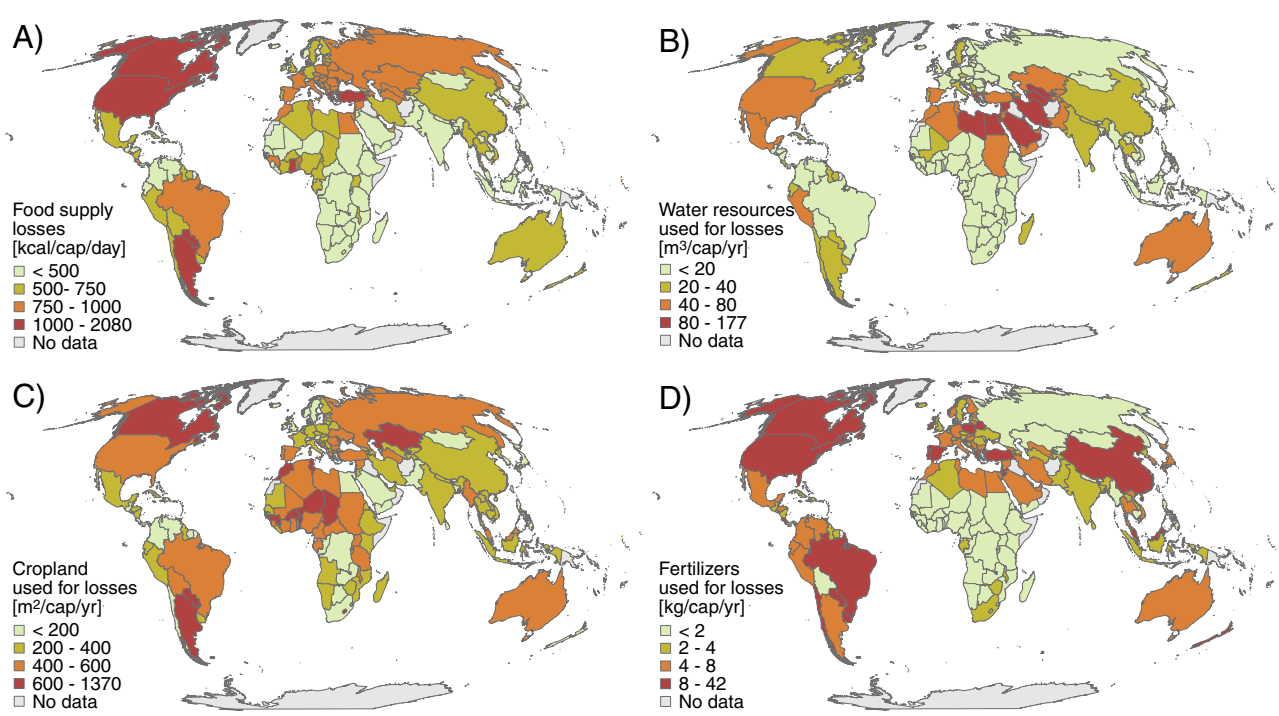

Fig. 3. Country results of A: food supply losses and waste; B: per capita water resources used for FSC losses; C: per capita cropland area used for FSC losses; and D: per capita fertilisers use used for FSC losses (sum of N, P_2O_5, and K_2O). All the results are averaged over years 2005–2007.

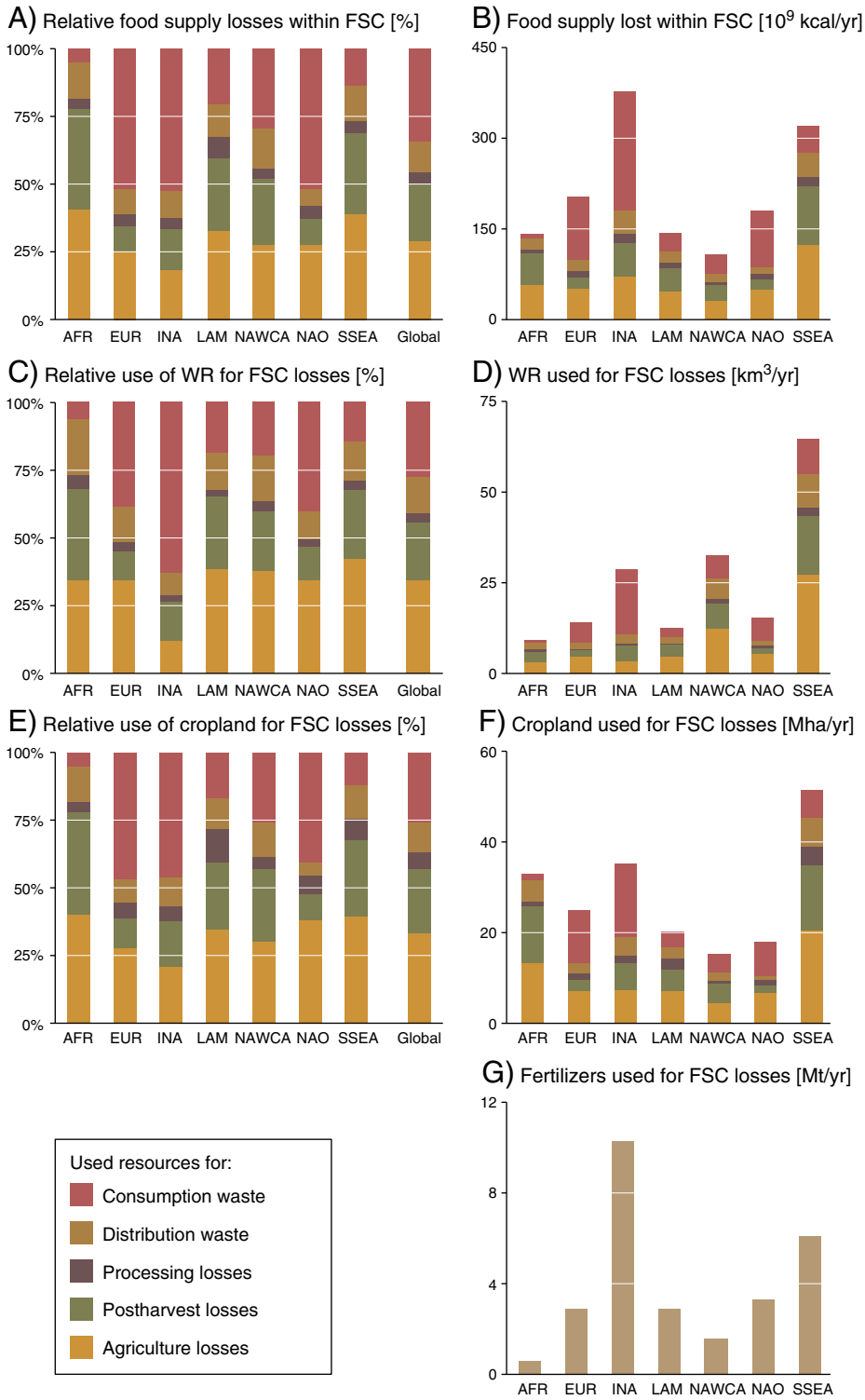

Fig. 4. Relative and absolute amounts of food supply losses and resources used for these losses per FSC (food supply chain) categories averaged over years 2005–2007. A: Relative food supply losses; B: food supply losses; C: relative use of water resources (WR); D: volume of water resources use; E: relative use of cropland area; F: area of cropland use; and G: amount of fertilisers use (sum of N, P_2O_5, and K_2O) (note: only the total amount is shown due to data limitations; see Section 3.4). AFR stands for Sub-Saharan Africa, EUR for Europe (including Russia), INA for Industrialised Asia, LAM for Latin America, NAWCA for North Africa & West-Central Asia, NAO for North America & Oceania, and SSEA for South & Southeast Asia. See tabulated per capita regional results in Table S4 of the Online Supplements.

most of the global irrigation water is used for these products (Siebert and Döll, 2010). We only found moderate differences between the regions, although cereal related losses have a large share of total FSC losses in Industrialised Asia, whilst losses related to fruits & vegetables are very high in Latin America (Fig. 5B).

4.3. Use of cropland and fertilisers for the FSC losses

Of the total cropland area, 56% is used for the products consumed by humans whilst the areas used for feed and FSC losses account for 20% and 17% respectively (Fig. 2C; Table S3). In Europe and North

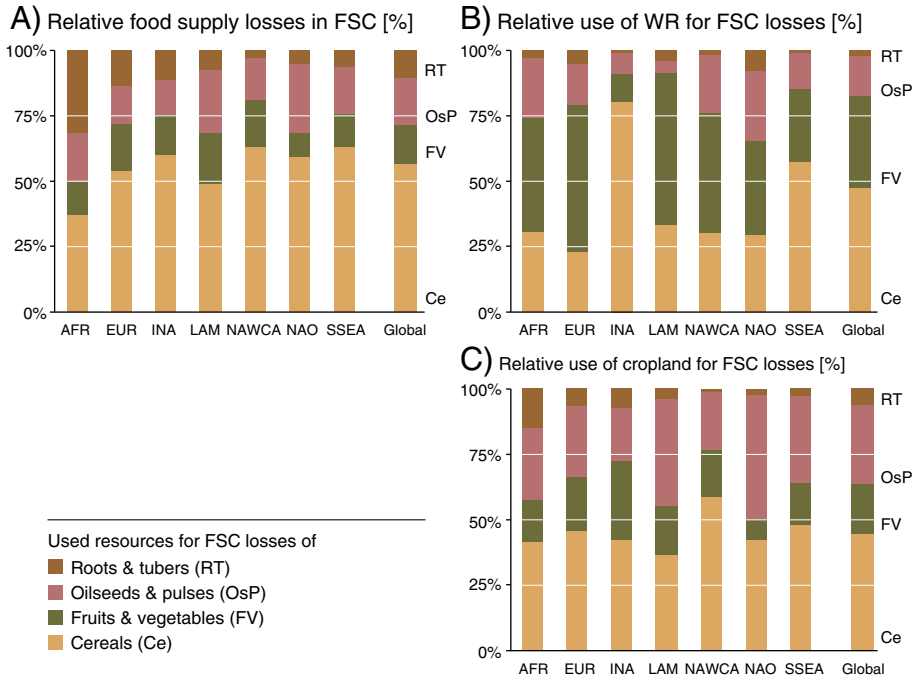

Fig. 5. Relative amounts of food supply losses and resources used for FSC (food supply chain) losses per commodity group averaged over the years 2005–2007. A: Relative food supply losses; B: Relative use of water resources (WR); C: Relative use of cropland area. Note: relative use of fertilisers is similar to the use of cropland area (see Section 3.4). AFR stands for Sub-Saharan Africa, EUR for Europe (including Russia), INA for Industrialised Asia, LAM for Latin America, NAWCA for North Africa & West-Central Asia, NAO for North America & Oceania, and SSEA for South & Southeast Asia.

America & Oceania, the area used for animal feed (39% and 37% respectively) is approximately equal to that used for products consumed directly by humans. By comparison, in South & Southeast Asia only 8% of the cropland area is used for products directed to feed.

Altogether, 866 Mha/yr of cropland and 118 Mt/yr of fertilisers are used to produce the analysed food products directed to human food. Approximately 77% of this area is used for products consumed as human food, and 23% is used for FSC losses (Fig. 2C). The FSC losses correspond to 198 Mha/yr (30.5×10^{-3} ha/cap/yr) of cropland and 28 MT/yr (4.3 kg/cap/yr) of fertilisers (Table 2). The largest per capita cropland use for FSC losses occurs in the North America & Oceania region (50×10^{-3} ha/cap/yr), and the smallest in Industrialised Asia (24×10^{-3} ha/cap/yr) (Table 2). The largest losses relative to total cropland use also occur in North America & Oceania (31%), where the per capita fertiliser use for FSC losses is also greatest (9.3 kg/cap/yr) (Table 2). Proportionally, the use of nutrients for FSC losses is also largest in North America & Oceania (30%) (Table 2). The country level data are presented in Fig. 3C for cropland use and in Fig. 3D for fertilisers use.

Globally, postharvest and agricultural losses have a slightly larger role in cropland use than water resources use (Fig. 4). Although South & Southeast Asia also has the largest absolute cropland use for FSC losses (Fig. 4F), the difference in relation to other areas is less than is the case of freshwater resources. In the case of fertilisers, Industrialised Asia is the largest user (in absolute terms) of nutrients for FSC losses (Fig. 4G).

In terms of different kinds of crops, cereals account for approximately 45% of cropland area used for FSC losses. Fruits & vegetables and oilseeds & pulses account for 19% and 30% of that area respectively, whilst roots & tubers are the smallest with a 6% share (Fig. 5C). There are no notable differences between the regions.

4.4. Potential of improved efficiencies in the food supply chain

Under the minimum loss scenario (i.e. if lowest loss and waste percentages achieved in any region in each step of the FSC would be achieved globally), our results suggest that approximately half of the FSC losses (in terms of food supply) could be prevented compared to the current situation (Table 3). Globally, the largest potential for improvements is in agricultural losses and consumption waste. Agricultural losses could be reduced globally by 47% (varying regionally between 25% and 59%) compared to baseline, and consumption waste could be reduced by 86% (varying regionally between 0% and 94%). The postharvest losses have the smallest potential for improvements, with only a 4% reduction globally based on our scenario. This is because postharvest loss percentages are very similar in all the regions, whilst there are greater regional variations for agricultural losses and consumption waste percentages (see Gustavsson et al., 2011; pages 26–27).

By region, the largest potential reductions in terms of food supply are in North America & Oceania (63%) and Europe (63%), and the smallest potential reduction is in Sub-Saharan Africa (31%). These regional differences in the potential of reducing FSC losses originate mainly from the nature of existing losses and waste in different regions. In Sub-Saharan Africa, for example, the consumption losses are very low compared to the industrialised regions (Gustavsson et al., 2011; Parfitt and Barthel, 2011; Parfitt et al., 2010) whilst there is less difference in agricultural loss percentages.

In terms of water resources, the water use for FSC losses could be reduced by 44%, i.e. from 27 m^3/cap/yr to 15 m^3/cap/yr (Table 3). The reduction potential for water resources is largest in Industrialised Asia (59%) and smallest again in Sub-Saharan Africa (27%) (Table 3). Moreover, 39% of the cropland used for FSC losses (total losses reduced from 198 Mha/yr to 121 Mha/yr) and 42% of fertiliser resources used for FSC losses (from 28 Mt/yr to 16 Mt/yr) could be saved under the minimum loss scenario (Table 3).

5. Discussion

Around one quarter of the global food crops, in terms of food supply, are lost or wasted. This loss amounts to 1.46×10^{15} kcal/yr, which would be enough to feed around 1.9 billion people assuming a 2100 kcal/cap/day food supply level (stated as the amount of daily kilocalories needed for an average person to lead a healthy life by WHO,

Table 3
Summary of the 'minimum loss' scenario results at the regional scale for food supply and analysed resources (water resources, cropland, and fertilisers). Baseline corresponds to resources used for FSC losses under the current situation and scenario for resources used for FSC losses under the minimum loss scenario conditions. All the results are averaged over the years 2005–2007. AFR stands for Sub-Saharan Africa, EUR for Europe (including Russia), INA for Industrialised Asia, LAM for Latin America, NAWCA for North Africa & West-Central Asia, NAO for North America & Oceania, and SSEA for South & Southeast Asia. Note: some countries are missing from the analyses due to data constraints (see Figure S1 in the Online Supplements for missing countries, regional delineation, and region abbreviations); totals may not sum up due to rounding.
Source for population data: FAOSTAT population module (FAO, 2011b).

Region	Popul. ($\times 10^6$)	Food supply		Water resources		Cropland		Fertilisers (nutr.)	
		Baseline	Scenario	Baseline	Scenario	Baseline	Scenario	Baseline	Scenario
		[kcal/cap/day]	[kcal/cap/day]	[m^3/cap/yr]	[m^3/cap/yr]	[m^2/cap/yr]	[m^2/cap/yr]	[kg/cap/yr]	[kg/cap/yr]
AFR	766	506	351 (−31%)	12	9 (−27%)	431	315 (−27%)	0.7	0.5 (−28%)
EUR	749	720	266 (−63%)	18	9 (−53%)	334	152 (−55%)	3.9	1.8 (−53%)
INA	1518	678	314 (−54%)	19	8 (−59%)	232	133 (−43%)	6.8	3.9 (−43%)
LAM	559	693	404 (−42%)	22	13 (−42%)	361	235 (−35%)	5.2	3.3 (−36%)
NAWCA	378	775	375 (−52%)	86	46 (−46%)	407	218 (−47%)	4.2	2.3 (−46%)
NAO	357	1334	495 (−63%)	42	18 (−57%)	498	232 (−53%)	9.3	4.2 (−54%)
SSEA	2168	404	270 (−33%)	30	20 (−34%)	237	166 (−30%)	2.8	2 (−31%)
Global	**6495**	**614**	**320 (−48%)**	**27**	**15 (−44%)**	305	**187 (−39%)**	**4.3**	**2.5 (−42%)**

2012). If the target of the European Parliament (2012) to halve food losses and waste by the year 2025 within the European Union area were to be applied globally, almost one billion more people could be fed. This would be enough to meet the need of the global population growth between now and then, based on the medium variant of the UN estimation for global population is for the year 2025 (UN, 2011), i.e. increase of global population by around 1.0 billion from today's ca. 7.0 billion.

The potential for improvements in FSC efficiency is, however, largest in regions where there is least need for extra food supply (Table 3), and smallest in regions with the largest challenges in terms of malnutrition and population growth (Sub-Saharan Africa and South & Southeast Asia). Nevertheless, these two regions still have much potential to improve in FSC efficiency (31% and 33% respectively, according to our scenario) and therefore potential for significant increases in food supply with the currently used natural resources.

Of the total freshwater, cropland, and fertiliser resources used in food crop production, one quarter of the freshwater and one fifth of the cropland and fertilisers are used to produce these FSC losses. In this section we discuss the significance of these results, how these food and resource losses and waste could be avoided, and several limitations of our study that should be taken into account when interpreting our results.

5.1. Freshwater use for FSC losses in relation to available resources

The freshwater resources used for FSC losses account for 215 km^3/yr, which is around 12–15% of the global consumptive water use (Döll et al., 2012; Wada et al., 2011). At the same time, approximately 35% of the global population is living under high water stress or shortage (e.g. Kummu et al., 2010). Water use for FSC losses as a percentage of total available freshwater resources (FAO, 2011a) is particularly high for countries in the dry North Africa & West-Central Asia region (>5% of available resources) and the highly populated South Asia region (1–5%) (Fig. 6). In the rest of the world, this percentage is less than 1%, except for in Mexico, South Africa, Spain, Turkey, and a few small European, African, and Caribbean countries (1–5%). In three countries, the use of water resources for FSC losses exceeds the available resources, namely Kuwait (595% of the national renewable water resources), Saudi Arabia (115%), and United Arab Emirates (222%) (Fig. 6). These three countries have limited national water resources (FAO, 2011a), and therefore they have to import a major part of their consumed agricultural products (FAO, 2011d).

5.2. Cropland and fertiliser use for FSC losses

The total cropland use for FSC losses (198 Mha/yr) almost equals the extent of cropland in Africa (221 Mha) and is larger than the

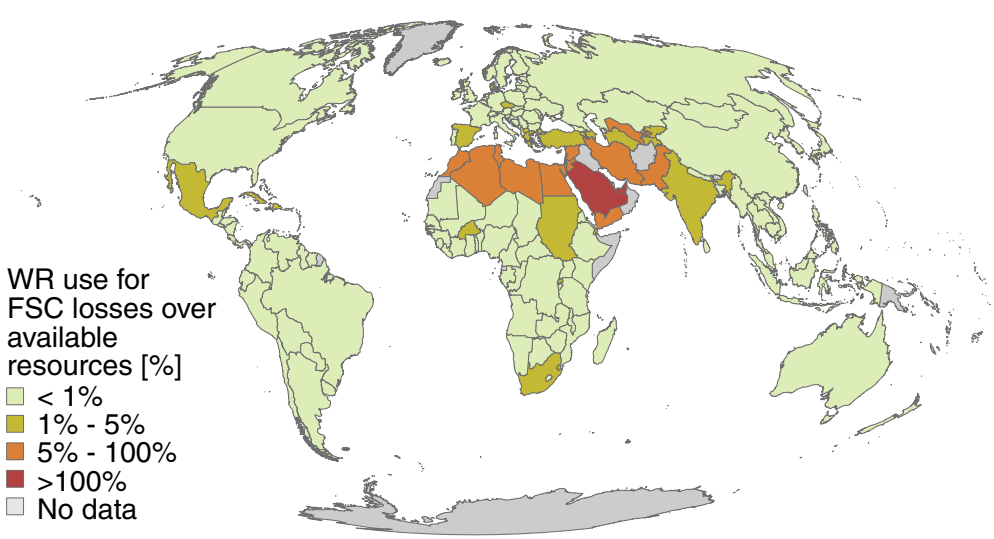

Fig. 6. Percentage of water resources (WR) use for FSC losses over national renewable water resources. Data source for national renewable water resources: AQUASTAT database (FAO, 2011a).

total expansion of global cropland over the last 60 years (FAO, 2011f). Reducing FSC losses in line with the 'minimum loss' scenario could potentially save 78 Mha of cropland, which is more than the total extent of cropland in a country like Brazil (61 Mha) or the whole of Southeast Asia (66 Mha). Similarly, total fertiliser use for FSC losses (28 Mt of nutrients per year) is larger than the current fertiliser application in Africa and Europe together, and the potential reduction of the losses (12 Mt/yr) represents the current use of fertiliser in Brazil (11 Mt/yr) or the whole of Southeast Asia (11 Mt/yr) (FAO, 2011f). These findings highlight again the huge potential that a more efficient FSC holds for saving valuable resources.

5.3. Reducing FSC losses for sustainable intensification of food production

Previous research has highlighted the importance of irrigation and fertilisation for increasing crop yields (Foley et al., 2011; Siebert and Döll, 2010) and reducing yield gaps (Licker et al., 2010; Neumann et al., 2010). By using these management practices, less cropland is required to produce the same amount of crop. Consequently, the cropland resource is replaced partially by an increased use of the resources of water and crop nutrients. Our results indicate that FSC losses and related resource losses are large (even in relative terms) in regions with intensive production systems and a large per capita food supply (e.g. North America & Oceania) and low in regions with a small per capita food supply (e.g. Sub-Saharan Africa or South & Southeast Asia) (Table 2) indicating differences in the efficiency of the FSC and/or differences in resource use efficiency.

There is no doubt that a further intensification of agricultural production will be required in the coming decades to cope with the increased demand for biomass products (Cirera and Masset, 2010; Godfray et al., 2010). To reduce negative impacts of this development on the environment (greenhouse gas emissions, water scarcity), it will be necessary to increase the efficiency of the FSC. Pathways of a sustainable intensification of the production system, such as a more strategic use of fertilisers, technology improvements, and technology transfer, are discussed for example by Tilman et al. (2011), but need to be extended to the whole supply chain.

5.4. Comparison to previous research

In terms of weight, we found that around one third of the total global food crop production is lost or wasted in the FSC. This is well in line with the overall results of Gustavsson et al. (2011), whose loss and waste percentages we used in our calculations. The amount of waste (in terms of weight) is also in line with their study at both the regional and global scale (Table S5 in the Online Supplement), taking into account differences in study setup (see Table S6 in the Online Supplement). For example, we analysed only crop products whilst Gustavsson et al. (2011) analysed both meat-related and crop products. Globally, around 84% (weight-wise) of the food production analysed by Gustavsson et al. (2011) is of non-meat products (i.e. the products we included in our study). This varies regionally from 75% in Europe to 94% in Sub-Saharan Africa. This and other differences (Table S6) should be taken into account when comparing the results of these two studies.

5.5. Limitations of the study

Our analyses involved several assumptions and simplifications, as presented and discussed in the Methods section. Given these limitations, we highly recommend limiting the use of the results to the macro-scale (i.e. regional to global).

A major source of uncertainty is related to the regional loss and waste percentages used for our calculations. The original data for loss and waste percentages, taken from Gustavsson et al. (2011), are regional, and differences between countries within the same region are not taken into account. Furthermore, in some regions the observed data are scarce, and thus Gustavsson et al. (2011) needed to make various assumptions when estimating the loss and waste percentages. Still, we believe that their estimates are the best currently available at the global scale, and therefore a good basis for our calculations.

Another possible source of error is the simplified method used to calculate the use of resources for imported commodities. We used the average water footprint and crop yield of all the exported products for the imported commodities and not the value of the country from where the product was imported, as the latter data are not always available (for example due to re-exporting). This impacted the last three steps of the FSC, as the agricultural and postharvest losses are assigned to the country in which the commodity was produced.

To account for crop specific differences in FSC losses, we used crop specific harvested area to compute the use and potential savings of cropland. This results in underestimates of cropland use for FSC losses (and for the related potential savings) in regions with a low cropping intensity, and overestimates in multi-cropping regions. At the global scale, harvested crop area is about 20% smaller than cropland extent (Siebert et al., 2010), indicating that we may slightly underestimate cropland use (and thus potential savings).

Our calculations of the potential savings of fertilisers by a more efficient FSC neglect the fact that synthetic fertilisers represent only a part of the total nutrient intake of cropland, and that FSC losses therefore also cause waste of nutrient inputs from other sources. For example, N-fertilisers provide about half of the total N-inputs to the world's cropland (Liu et al., 2010; Potter et al., 2010; Smil, 2002). Therefore, a reduction of FSC losses, and a related decline of the related N-losses from other sources, indicates that the potential for savings of synthetic N-fertilisers might be even larger than estimated in this study.

We acknowledge that the realisation of parts of our idealised minimum loss scenario may not be feasible in all regions. This could be in part due to physical geographical differences between regions. For example, in regions where soils or hydro-climate provide marginal conditions for food production, pre-harvest losses may be more difficult to reduce than in prime agricultural areas. The achievement of loss reduction is further complicated by economic, political, and social factors (see also Table 1). For example, in economic terms it may not be efficient to reduce losses in all parts of the FSC. Political and regulatory aspects may also limit the potential to reduce food losses. Finally, cultural preferences and habits play a major role in the feasibility of reducing losses and waste, such as the motivation of individuals, households, and businesses to reduce their own waste. Hence, we suggest that future scientific research and policy development should examine both: i) which food loss and waste reductions can physically be obtained in different regions; and ii) the means of achieving these, which should be tailored to local political, economic, and cultural conditions.

Finally, it should be noted that parts of the food losses, and particularly food waste, are used for other purposes, such as animal feed and biofuel production. Thus, although FSC losses are not used directly by humans, a share of those losses and waste are utilised for other purposes and not totally lost.

6. Conclusions

In this article, we analysed for the first time global scale food supply losses (in terms of kcal) due to lost and wasted food crops, and the amount of natural resources (freshwater, cropland, and fertilisers) that are used to produce them. Our findings emphasise the importance of reducing food losses and waste, as around one quarter of the total produced food supply is lost within the FSC. Equally, around one quarter of the consumed water resources, cropland, and fertilisers are used to produce these losses. We estimate that approximately half of the food supply losses, and the associated resources used to produce those, could be saved by applying everywhere the

current minimum loss and waste percentages in each FSC step. If the FSC losses could indeed be halved, an extra one billion people could be fed with adequate food supply, and in addition critical resources could be preserved.

Based on our results, the potential to reduce FSC losses is considerable, implying that reducing FSC losses could be a significant step towards a more sustainable use of the resources used in its production. The reduction of food losses and waste therefore offers possible new solutions to ease the challenges in resource scarce areas and societies suffering malnourishment. Moreover, it might bring many new entry points to technological development and innovations. Therefore, we strongly encourage scientists, policy-makers, as well as producers and consumers of food, to pay more attention to reduce food losses and waste in the FSC. We believe that these reductions could lead to a significant increase in water and food security in many parts of the world. Moreover, reducing losses would also have several important secondary benefits, such as reducing greenhouse gas emissions, conserving energy, protecting soil from degradation, and decreasing pressure for land conversion into agriculture and therefore also protecting biodiversity and carbon sinks.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2012.08.092.

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