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Quantifying food losses and the potential for reduction in Switzerland

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ABSTRACT

A key element in making our food systems more efficient is the reduction of food losses across the entire food value chain. Nevertheless, food losses are often neglected. This paper quantifies food losses in Switzerland at the various stages of the food value chain (agricultural production, postharvest handling and trade, processing, food service industry, retail, and households), identifies hotspots and analyses the reasons for losses. Twenty-two food categories are modelled separately in a mass and energy flow analysis, based on data from 31 companies within the food value chain, and from public institutions, associations, and from the literature. The energy balance shows that 48% of the total calories produced (edible crop yields at harvest time and animal products, including slaughter waste) is lost across the whole food value chain. Half of these losses would be avoidable given appropriate mitigation measures. Most avoidable food losses occur at the household, processing, and agricultural production stage of the food value chain. Households are responsible for almost half of the total avoidable losses (in terms of calorific content).

1. Introduction

Food loss over the entire food value chain represents a significant loss of resources invested in food production, transport, and storage. Since resources (land, energy, fresh water, agricultural inputs) are limited in nature, they should be applied efficiently and sustainably. Further negative externalities of food production include ecotoxicity from pesticides, eutrophication, soil erosion, organic matter loss, and biodiversity loss (Pretty, 2005). Between 20% and 30% of the environmental impact of products is caused by food consumption (Tukker et al., 2006). Thus, food loss may cause substantial environmental impact. Furthermore, economically avoidable food losses are of high importance in the efforts to combat hunger and to improve food security, not only in developing but also in developed countries. Improving the efficiency of the food value chain could help bring down the cost of food to the consumer and thus increase access for low-income households (Gustavsson et al., 2011). A multidisciplinary research project in the UK found that reducing food losses across the entire food value chain will be a critical component of any strategy to sustainably and equitably feed the rapidly growing global population (Foresight, 2011).

A survey from the Swiss Federal Institute of the Environment (Baum and Baier, 2008) analysed the flows of biogenic goods in Switzerland. The results show that 1.8 mio. tonnes of plant products and 0.1 mio. tonnes of animal products (dry matter) were consumed in 2006. Baum and Baier (2008) also analysed various flows of disposal, but without differentiating between food and other biogenic goods. The most extensive statistical analysis of food consumption in Switzerland is carried out annually by the Swiss Farmer's Union (SBV, 2009). The analysis encompasses agricultural production, import, export, storage variation, and consumption at the retail level.

Two recent publications estimate food losses over the entire food value chain from agricultural production to final consumption. According to Lundqvist et al. (2008), 1400 kcal/capita are lost globally every day. Gustavsson et al. (2011) differentiates between seven regions, one of them being Europe. Here, the avoidable losses are estimated at 280 kg/cap/a.

A "preparatory study on food waste across the EU 27 Member States" (Monier et al., 2010) estimates the food losses in each country, based on the EUROSTAT database, a literature review, stakeholder consultations, and specific hypotheses. The losses over all stages of the food value chain except agricultural production are estimated between less than 50 kg/cap/a (Greece) and more than 500 kg/cap/a (Netherlands), with an average of 180 kg/cap/a for EU 27. The major contribution is from households (42%).

The most recent study at a national level was carried out in Germany, induced by a report of the European Parliament on how to avoid food losses and on strategies for a more efficient food value chain in the EU (Caronna, 2011). The study quantifies the amount of food losses over all stages of the food value chain except agricultural production. They estimate food losses in Germany to be between 8 and 15 mio. tonnes per year (100–180 kg/cap/a, calculating with a population of 82 mio.). The major contribution is

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from households (61%), followed by the processing and the food service industry (17% each) (Kranert et al., 2012).

In Switzerland, quantitative data about food loss is incomplete and rare. A market study from 2001 by McKinsey & Company estimated the losses from the retail sector, based on the consultation of several food companies. The result gives a rough estimate of 14–36 kg/cap/a (numbers refer to fresh substance); 10% of this amount is estimated to fulfil qualifications for food donation to underprivileged people (Schweizer-Tafeln, 2010). In the Canton of Aargau, 21 kg/cap/a were wasted in 2007 from the food service industry alone (Baier and Reinhard, 2007). In the Canton of Bern, the corresponding amount has been estimated at 19.4 kg/cap/a in 2005 (Andrini and Bauen, 2005).

Data on food losses in Swiss households are lacking, despite their importance. A large study performed in the UK, based on a physical waste analysis of 2138 households, illustrated that the avoidable and possibly avoidable losses correspond to 17.7% of the weight of the food and drink purchased; the food losses, excluding drinks, make up 21.3% of the purchases (Quested and Johnson, 2009). Another study in Germany, based on online diaries in 200 households, concluded that 12% of food purchased by households is lost (Cofresco, 2011).

The goals of this paper are: (a) to quantify the scale of food loss in Switzerland across the entire food value chain from agricultural production (harvesting) to final consumption (intake) and with differentiation into a number of relevant food categories, (b) to group them into avoidable, possibly avoidable, and unavoidable losses and (c) to suggest some initial measures for the reduction of food losses.

2. Methodology

2.1. Definitions

In the literature food losses are defined in different ways. The definition employed in this paper refers to food which is originally produced for human consumption but then directed to a non-food use or waste disposal (e.g. feed for animals, biomass input to a digestion plant, disposal in a municipal solid waste incinerator).

Food losses are grouped into three categories, based on the definitions in Quested and Johnson (2009):

(1) *Avoidable losses* refer to food and drink thrown away because they are no longer wanted, e.g. because they perished or exceeded their date of expiry. Most avoidable losses are composed of material that was, at some point prior to disposal, edible, even though a proportion is not edible at the time of disposal due to deterioration (e.g. rotting, decomposition).
(2) *Possibly avoidable losses*, in contrast, refer to food and drink that some people eat and others do not (e.g. apple peels), or that can be eaten when prepared in one way but not in another (e.g. potato or pumpkin skins), or that is sorted out due to specific quality criteria (e.g. bent carrots).
(3) *Unavoidable losses* comprise waste arising from food and drink preparation that is not, and has not been, edible under normal circumstances. This includes apple cores, banana skin, tea leaves, coffee grounds, and inedible slaughter waste. Additionally, harvesting, storage, transportation, and processing losses that are not avoidable with best available technologies and reasonable extra costs are also classified as unavoidable (see also SI, Section 4.19).

This definition of *food losses* differs from that in Gustavsson et al. (2011) by including the *unavoidable losses*, which are omitted in the cited study.

According to Gustavsson et al. (2011), *food waste* is often used for *food losses* occurring at the end of the food value chain (retail and final consumption), where most losses are caused by wasteful behaviour. Nevertheless, in this paper both terms are used synonymously and refer to all *food losses*, because a distinction between wasteful behaviour and other reasons for *food losses* was difficult to perform.

The *food value chain* is the system of organizations, people, and activities involved in moving food from its producer (usually the farmer) to the consumer. In the present work, it also comprises the consumption phase itself and losses that occur at the end consumer.

For the present study, a multitude of data sources was used. Background information about these sources, data quality and calculations is provided in the electronic supplement information, referenced as “SI” (http://dx.doi.org/10.1016/j.wasman.2012.11.007).

2.2. Data acquisition

Table 1 contains an overview of the numbers and types of organisations that provided data about food losses. In order to model the whole food value chain, several data gaps had to be filled with data from the literature and with additional assumptions (details in the Supplement information (SI), Chapters 1 and 4).

2.3. Food categories

In this paper 22 food categories are analysed (Table 2). The categories were defined according to their importance for the Swiss consumer basket and characteristics regarding food losses. For example, berries were defined as separate category because of their high perishability, although they only contribute 0.2% of the calories of total food consumption. In order to avoid double counting of ingredients, the food categories were defined at the level of ingredients. For example, in the category of breads and pastries only wheat was modelled; the other ingredients like sugar and eggs were attributed to other categories.

2.4. System boundary

The analysis in this paper covers the entire food value chain that is related to Swiss food consumption, from agricultural production to the consumer. Food waste in other countries, resulting from the production of food imported for consumption in Switzerland, was included in the analysis, assuming the loss rates to be equal to production in Switzerland. Food waste resulting from the production of food for export was not included. Agricultural production was defined as potential crop yield in edible quality at the time of harvest in the present farming system, including inedible parts that are separated later in the food value chain (e.g. apple cores, peel-

Table 1
Overview of the number and types of firms, institutions and associations providing data (the number of organizations is shown in parentheses). Details about the individual data providers are given in Table S1 in SI.

FIRMS (31)
Agricultural producers (5)
Food trading and logistics industry (5)
Food processing industry (6)
Food service settings, e.g. restaurants (2; data from 201 settings)
Retailers (4)
Bakeries (5; data from 29 branches)
Food banks (4)
Trade and Producer Associations, e.g. farmers’ union (10)
Federal Institutions, e.g. federal statistical office (3)

Table 2
Food categorisation. The second column quantifies Swiss food consumption at the retail level (input to households and catering trade), the third column the average calorific content of each food category.

Food category	Consumption per year (2005–2007) (tonnes of fresh substance/a)	Calorific content (kcal/100 g)
Fruits		
1. Apples	121,483	52
2. Fresh fruits excluding apples and berries	388,538	52
3. Berries	49,757	43
4. Canned fruits	24,894	70
Vegetables		
5. Potatoes	339,860	77
6. Fresh vegetables	417,807	37
7. Storable vegetables	139,269	37
8. Processed vegetables	131,824	36
Cereals		
9. Bread wheat (Breads and pastries)	392,332	359
10. Durum wheat (Pasta)	87,580	370
11. Rice	39,249	358
12. Maize	11,542	366
Sugar		
13. Sugar	323,581	402
Oils and fats		
14. Oils and fats	174,249	908
Dairy		
15. Milk/other dairy products	1,246,686	59
16. Cheese	199,970	271
17. Butter	77,775	767
Eggs		
18. Eggs	83,506	162
Meat		
19. Pork	186,119	378
20. Poultry	72,310	172
21. Beef and other meat/offal	116,742	243
Fish		
22. Fish	64,848	152
Total	5,142,173	158

ings). For milk and eggs, the point of reference was the edible amount at the time of milking or laying eggs. For meat, it was the whole body of the animals at the time of slaughtering, for fish at the time of harvest. Suboptimal yields due to suboptimal farming systems and losses that are not avoidable with current best available technologies and reasonable extra costs were not accounted for in this analysis.

2.5. Assessment of data reliability

The quality of each data source was assessed according to the pedigree matrix used in the ecoinvent database v2.0 (Frischknecht et al., 2007). Losses were defined for each food category and each stage of the food value chain. For loss entries that originate from several references, each reference was assessed separately for its *reliability* and its *temporal, geographical,* and *technological correlation*. However, *completeness* and *sample size* were assessed once for all the references of a loss entry. Assessment details are described in SI, Section 5, and an overview of the assessment of each reference can be found in Tables S9 and S10 in SI.

2.6. Derivation of losses

The following sections describe for each stage of the food value chain how the shares of loss are calculated and estimated. Detailed information about the derivation of food losses for each food category is available in the Supplement information (Chapter 4 and Tables S11 and S12); an overview of the stages of the food value chain from agricultural production to consumption is provided in Fig. 1.

Storage losses were attributed to the phase in which they occurred. For example, the storage losses of a producer of fresh pasta were attributed to processing, the storage losses of an apple trader to postharvest handling and trade, and the storage losses on farms to agriculture.

2.6.1. Production losses

Losses during crop production are highly variable, depending on the geographical region, season, weather, type of crop, and on its cultivation and harvest method. Due to the high variability and lack of data, it is difficult to determine reliable values. The losses of vegetables, cereals, oils and fats, and the losses of dairy products and eggs were estimated from five farmers from the regions of Basel and Zurich and from Gustavsson et al. (2011), which estimated the average losses for Europe. The fruit losses caused by quality standards in agriculture were estimated by a Swiss fruit trading firm; the losses from fruit trees that are not harvested were ignored. For meat production, the losses due to illnesses were estimated by a farmer (Tannenhof, 2011) and the slaughterhouse waste resulting from the production of pork and beef was based on the measurements of a Swiss slaughterhouse (SBA, 2011). The losses of chicken were based on estimations by the centre of competence of the Swiss poultry industry (Aviforum, 2011).

2.6.2. Losses in postharvest handling and trade

The fruit and vegetable losses in postharvest handling and trade were analysed using data from two major trading companies and a minor vegetable trader. The losses for other food categories were roughly estimated, based on farmers' interviews, on data from a supplier of food service settings, and on the FAO's estimates for Europe (Gustavsson et al., 2011).

2.6.3. Processing losses

The estimations and measurements were based on data from eight firms engaged in the fields of vegetable and fruit processing, pasta and sugar manufacturing, baking, and dairy processing. The firms were assumed to be representative for the Swiss market. In other fields of food processing, data from literature and from public institutions was used.

2.6.4. Losses in the food service industry

In the food service industry, data from two studies (Andrini and Bauen, 2005; Baier and Reinhard, 2007) and from *SV Group* (SV Group, 2011) was considered. *SV Group* has done measurements of food waste in 225 out of its more than 300 restaurants and bars; Baier and Reinhard's study is based on data from 40 food service installations; Andrini and Bauen's study on data from 20 restaurants. The mentioned studies include restaurants, canteens, bars, cafeterias, care homes, hospitals, and military institutions. Compared to the Swiss average, staff restaurants and canteens are over-represented (Gastrosuisse, 2011; SV Group, 2011). Nevertheless, no correction was made because the losses of the analysed staff restaurants and canteens do not substantially differ from the average losses of all food service installations. However, gourmet restaurants are lacking in the mentioned analysis. Therefore, a separate analysis of the gourmet restaurant *Stucki* was undertaken. The plate and kitchen waste of one day (49 guests) was collected, sorted according to its avoidability, and weighted. The percentage of the waste's weight and the total food consumed was calculated (Stucki, 2011). The losses in the gourmet restaurant *Stucki* were included in the calculation with a weight of 1%, based on the number of restaurants being members of the *Gilde* (178 with 3–4 crowns; Gilde, 2011) relative to the total number of food service installa-

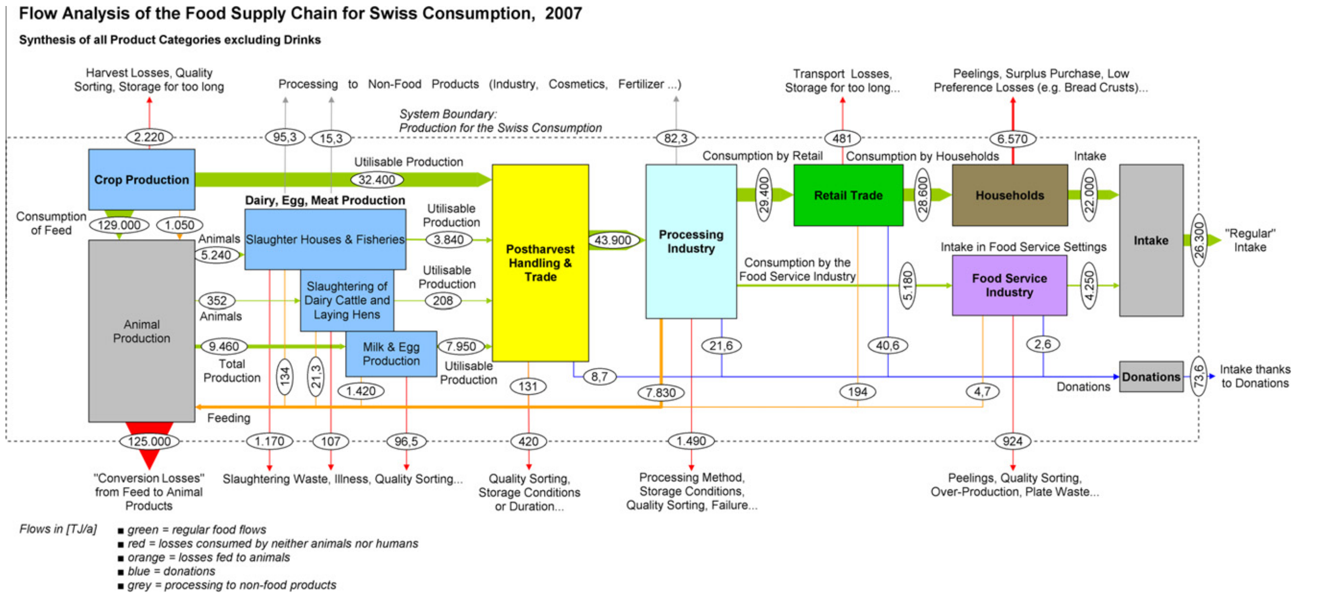

Fig. 1. Energy flow analysis of the food value chain destined to meet the Swiss food demand, including the net import of products. Green arrows illustrate the regular food flows leading to human consumption. Orange arrows represent food losses directed to livestock feed, grey arrows losses used for the generation of non-food products, red arrows display the remaining food losses, and blue arrows the food that is donated. The numbers are defined as TJ/a. The dotted line shows the system boundary, the boxes the stages of the food value chain.

tions in Switzerland (21,000 according to Gastrosuisse, 2011). Thus, although the values for the gourmet restaurants are based on only one restaurant, the large uncertainty within this sector will not be important in the overall analysis, due to the small share of 1% within the foodservice sector. Since Baier and Reinhard nor Andrini and Bauen did measure plate waste separately, we assumed the *SV Group's* numbers for plate waste to be representative for all restaurants except gourmet restaurants (Table 3).

The allocation of the losses in individual food categories, for plate waste, is based on the analysis of 1504 canteen guests' plate waste (ETH-Mensa, 2012); for kitchen waste the relative contribution of each food category is assumed to be equal to household waste (details in SI, Section 3.16).

2.6.5. Losses in the retail sector

Two supermarket chains and one discounter provided data to estimate the overall food loss in the retail sector. However, data from one of the supermarket chains only was available referring to one major branch; the other loss rates referred to all branches of the chains. The weighted average of the two supermarket chains was calculated, considering the proportions of their volumes of sales. Then, the weighted average of the supermarkets' losses and of the discounter's losses was calculated. The weighing refers to the proportions of the volumes of sales of the two major supermarket chains and the three major discounters in Switzerland. Only one retailer delivered quantitative data about its losses in detailed food categories and referring to all its branches. The relative composition of food losses between these food categories was multiplied to the overall losses to derive loss values per category also for the other retailers.

Particular attention was attributed to fruits and vegetables, because they are especially perishable. Here, we distinguished between losses in the stores and losses in the distribution centres.

The analysis of bread is a special case. Data from this category was derived not only from supermarkets, but also from five bakeries (details in SI, Section 4.15).

2.6.6. Losses in private households

Since no analysis of household waste in Switzerland was found, data from two English studies (Defra, 2010; Quested and Johnson, 2009) was adapted to the Swiss consumer basket by multiplying the loss rates per food category (Defra, 2010; Quested and Johnson, 2009) with the amounts consumed in Switzerland (SBV, 2009). The losses referring to mass were than converted to energy.

2.6.7. Allocation to methods of disposal and recycling

Reliable quantitative data about recycling and disposal is scarce in Switzerland. Thus, in the flow analysis, only a distinction between feeding and other losses was made (based on Spycher and Chaubert, 2011, and on SBV, 2009).

Table 3
Calculation of the losses in the food service industry. The original data is in *kilogram per person per year* and in *gram per meal*. The numbers are converted into *percentage of the total food input into the food service sector (including kitchen waste)*, assuming a portion size of 500 g/average meal (excluding kitchen waste) and a mean consumption of 166 meals/year/capita in food service installations (Baier and Reinhard, 2007; Statistisches Amt Aargau, 2009; SV Group, 2011). Possibly avoidable and avoidable losses include kitchen and plate waste.

Reference	Total losses	Unavoidable losses	(Possibly) avoidable losses	Weight
Baier and Reinhard (2007)	20.6 kg/cap/a	10% (10 kg/cap/a)	10.6% (10.6 kg/cap/a)	33%
Andrini and Bauen (2005)	19.4 kg/cap/a	2% (1.9 kg/cap/a)	17.5% (17.5 kg/cap/a)	33%
SV Group (2011)	115 g/meal	11.7% (70.7 g/meal)	7.4% (of which 2.9% plate waste) (44.3 g/meal)	33%
Average		7.9%	11.8% (of which 2.9% plate waste)	
Stucki (2011)	396 g/meal	29% (248 g/meal)	17.3% (of which 7.6% plate waste) (148 g/meal)	1%
Total weighted		**8.1%**	**11.8%** (of which 2.9% plate waste)	

Table 4
List of reasons for food losses considered in this paper, categorised by avoidability. Each loss record in the model was attributed to one of these reasons and thus defined as avoidable, possibly avoidable or unavoidable. The measures to avoid losses represent an incomplete set of suggestions from the authors. It should be further analysed how realistic the implementation of individual measures is.

Reason for losses	Description	Measures to avoid losses
I Avoidable losses		
Purchased too much	Buying more than is consumed before the food is no longer good to eat or runs past its consumption date	Pre-shop planning, avoid temptation of special offers and large portions
Left over after cooking	Cooking more than is consumed before the food is no longer good to eat or runs past its consumption date	Reduce cooking and warming portions
Left over after meal	Plate waste after meals, excluding inedible parts (bones...)	Reduce plate portions to the amount the person is sure he or she wants to eat
Stored for too long	Food decreased in quality, went mouldy or ran past consumption date	Optimise consumption prevision; advance booking; reduce the range of perishable products; donate; processing of products before running past consumption date; optimise storage conditions
• Too long on the retail shelves	Decreased quality, rotting (mainly fruits and vegetables)	
• Out of use-by / best-before date	Out of date because of being stored for too long in the retail shelves due to lower-than-expected demand or surplus stocks	
• Out of sell-by date		
Not harvested because of low demand	Crops not harvested because of low demand (mainly for highly perishable fruits and vegetables with little possibilities to be processed and with peaking crop yields, e.g. raspberries)	Consumers should be well informed about the seasonal offers AND consume in accordance with them
Over-production	To produce more than what can be consumed (served, sold, eaten) before the product goes off	Reduce production and preparation portions of perishable products and complement the offers by long-life or quickly prepared products; find distribution channels for surplus food
"Surplus" cocks	Male chicken in egg production (they are often gased, because meat production is less profitable with laying hens than with broilers)	Financial support of meat production with laying hens (hybrids); sex determination of eggs (currently under research)
Change in the production line	During the phase of switching from one product to another in a production line, unpure products can result (e.g. ravioli containing both spinach and mushrooms)	Reduce the frequency of product switches; find distribution channels for unpure products
Method of processing	Losses due to suboptimal method of processing	Apply best available technology
II Possibly avoidable losses		
Taste preferences	Wastage of edible parts of food because the person does not like its taste or smell or because of inappropriate methods of preparation (e.g. bread crust, potato skin, offal)	Adopt various methods of preparation; be less delicate; give unfavoured parts of food to other people
No demand because of reduced quality	Too long storage because of inferior quality (irrelevant in terms of food safety) and thus little demand, al-though the demand for this type of product is present (often aesthetic aspects)	Consumers: be less delicate and choosy; sellers: price reduction of substandard products
Quality sorting	Sorting out products because of high quality standards, although the products would be edible and healthy (often aesthetic aspects)	Find distribution channels for inferior quality (processing, price-reduction, donations)
III Unavoidable losses	Description	
Basic food sorting	Sorting out inedible products (generally inedible, not due to deterioration after harvesting)	
Manual harvesting	Losses associated with a specific, manual method of harvesting, not avoidable with reasonable extra costs (see also SI, Section 4.19)	
Technical harvesting	Losses associated with a specific, technical method of harvesting (best available technology)	
Contamination	Disposal of contaminated products	
Illness	Disposal of food due to crop or livestock illnesses	
Storage problems	Deterioration due to storage problems despite best available storage conditions (e.g. plant disease, mould)	
Failure	Deterioration due to a failure during preparation (e.g. burnt bread)	
Transportation	Deterioration due to transportation damage (despite best available technology)	
Inedible parts (apple cores, meat bones...)	Separation of inedible parts	
Method of processing	Losses caused by a specific method of processing, applying best available technology (e.g. weight loss of baking, by-products of apple juice production)	
Weather conditions	Damaged food due to bad weather conditions	

2.6.8. Attribution of avoidability

Each food loss record in the model was attributed to one of the reasons for losses listed in Table 4 and thus categorised as avoidable, possibly avoidable or unavoidable. The categories in Table 4 were developed during the process of data acquisition. Each new loss record was attributed to one of the previously defined reasons. Sometimes the attribution was evident. For example, unsold products in retail, that were wasted because they had been stored for too long, were classified as avoidable. In other cases, the allocation was less obvious. For instance, in the sorting process of apples, the distinction between rotten apples and apples sorted out because of aesthetical imperfections not tolerated by the quality standards is subjective. In some cases, quantitative information for the allocation was available, e.g. to distinguish the amount of plate waste and of inedible parts in the food service industry. However, most of the allocations were based on qualitative information from interviews with the experts providing food loss data (experts from the organisations listed in Tables S1 in SI). The boundary between edible and inedible food is often subjective. Tables S11 and S12 in SI link each loss to a reason and to its avoidability. Detailed explanations can be found in Chapter 4 in SI.

2.7. Mass and energy flow analysis and quantification of food efficiency

Data from firms of the food value chain were always specified as losses relative to the mass input and expressed in percentages. An overview of the losses in each food category and at each stage of the food value chain is displayed in SI, Tables S11 and S12. To model the absolute mass and energy flows for the supply of the Swiss food demand, including the net imports, data about Swiss food consumption had to be quantified for each of the 22 food categories analysed in this paper (see Table 2). Most data originates from the Swiss Farmer's Union (SBV, 2009) and refers to consumption at the retail level (input to households and to the food service industry). The share of home consumption versus consumption in the food service industry was derived in SI, Section 2; feed flows were based on the Swiss feed balance (SBV, 2009) and on Spycher and Chaubert (2011).

The mass flows were defined as fresh substance. They were also converted into energy flows indicating the energy available to human bodies. Data about the calorific content was taken from the Swiss Farmer's Union (SBV, 2009), from the feeding recommendations and nutritional tables for ruminants (Arrigo et al., 1999), and from a nutrient database (Yazio.de, 2011). The calorific content of slaughtering waste of cattle, swine, broilers, and laying hens was estimated based on its main components.

The food flows were calculated in Excel and then exported to STAN 2 (Cencic and Kovacs, 2007).

The efficiency of vegetarian products from harvest to final consumption depends on the amount of food loss in the food value chain. The efficiency of meat products, in contrast, first depends on the ratio of calorific output of the animal products for human consumption and the calorific input of the feed consumed by livestock. For poultry, for example, the analysis was based on typical feed consumption and typical meat yield per chicken. In the case of dairy and egg production, the output of the meat resulting as by-product was included in the reported efficiency. The subsequent losses in the food value chain, again, were calculated using data from the energy flow analysis.

3. Results and discussion

3.1. Energy flow analysis of all food categories

The energy flow analysis reveals that total crop production (food and feed, including foreign production for import to meet the Swiss food demand) amounts to 165,000 TJ per year. From this, 130,000 TJ (79%) are used as feed for animal production and only 32,400 TJ (21%) constitute the production of plant-based food. The comparison of the outputs of plant-based food and animal products, excluding the losses at the stage of production, gives the opposite pattern. Here, animal products only contribute 12,000 TJ (9% of the energy of the feed consumed). So, from the total agricultural output of plant-based and animal products, plant-based products make up 73% and animal products 27%, in term of energy supplied for human diets.

The highest absolute losses occur at the stage of processing. However, these losses are mainly unavoidable (see Section 3.2.3) and, in the end, mostly used for feeding. Households produce the highest losses that are not used for animal feeding. The final intake makes up only 16% of the calories of the food and feed grown on agricultural lands (Fig. 1).

The energy balance in Fig. 2 shows that from the net output of the stages agricultural and animal production (50,833 TJ), including slaughtering waste and postharvest losses, around 52% is finally ingested, while around a quarter is (theoretically) avoidable food loss. From this, nearly half is in perfect quality and discarded because of inefficient delivery from producer to consumer.

3.2. Losses at each stage of the food value chain

In this section, all loss values refer to the calorific content and are expressed as percentages of the input into the correspondent stage of the food value chain.

3.2.1. Production losses

In the production of plant-based and animal products, including slaughtering and fishing, the losses are estimated at 14%, thereof 5.5% being avoidable or possibly avoidable. The unavoidable losses are mainly technically induced harvesting losses and, for animals, slaughter waste. The avoidable and possibly avoidable losses are mainly caused by high quality standards and by unpredictable demand of fresh, perishable products.

3.2.2. Losses in postharvest handling and trade

The losses in postharvest handling and trade (e.g. damaged products from transportation or apples rejected due to unsatisfying quality) are estimated at around 1%. They are relatively low thanks to high technological standards in Switzerland.

3.2.3. Losses in the processing industry

The analysis reveals losses of processing of 21% in terms of energy, thereof 7% being avoidable. Avoidable losses mainly consist of wheat (high quality standards for baking), rice, whey, buttermilk, and other products with low demand. Besides quality criteria, the main reasons for losses of fresh products are assumed to be suboptimal organisation and coordination between actors, and high consumer expectations concerning the availability of a broad range of products.

3.2.4. Losses in the food service industry

The average food losses in the food service sector are estimated at 20% (Table 3). However, the losses vary up to a factor of 10 (Baier and Reinhard, 2007).

The amount of food losses is not suitable as a sole indicator for the potential to reduce food losses. Only a more detailed analysis of the restaurant, distinguishing between avoidable and unavoidable food losses, between kitchen and customer plate waste, and analysing the reason for losses, allows one to deduce measures how to reduce food losses. As an example, the losses of the analysed gourmet restaurant amount to more than 200% of the estimated average losses (Table 3). However, 44% of the losses in the gourmet restaurant are associated with the production of meat sauce (mainly bones); an additional 23% are inedible parts of fruits and vegetables. So, a large fraction of losses is unavoidable. This can be explained by the special preparation method of meat sauce, the preparation of fresh products, and by the high proportion of exotic fruits associated with large inedible parts (Stucki, 2011).

3.2.5. Losses in the retail sector, including bakeries

In supermarkets and discounters, the rate of unsold products is a good indicator for food losses because the fraction of unsold food that is not lost thanks to donation is less than 5%.[1] The rate of unsold food products varies between 1% and 5% between the retailers analysed, with an average of 2.2%. However, for individual food categories the range is larger (between 0% and 12%) and the rate for sin-

[1] In one of the most progressive supermarket chains in Switzerland in terms of food donations, the amount of donated food is estimated around 5% of the unsold products, assuming an average food price of 10 CHF/kg. Hence, the Swiss average of food donations in the retail sector is expected to be lower than 5% of the unsold products.

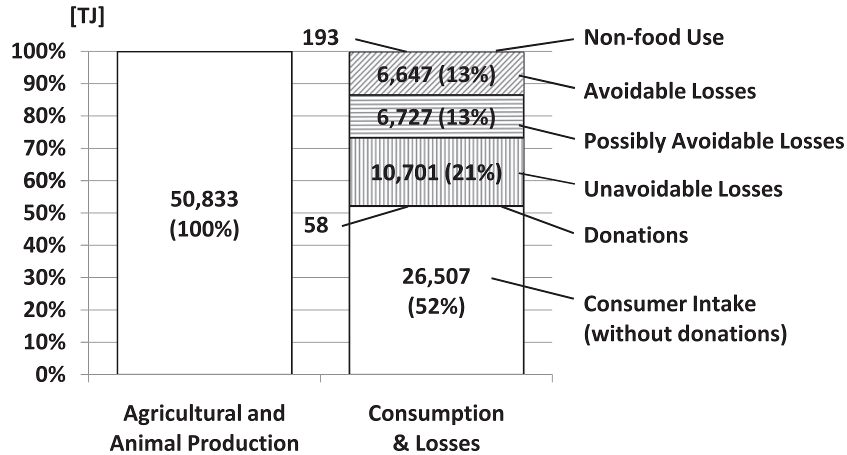

Fig. 2. Energy balance of the food produced to meet the Swiss food demand. The left column shows the net output agricultural and animal production, including slaughtering waste and inedible parts that are removed later in the production chain. In the right column, food consumption and food losses are displayed. Avoidable losses refer to inefficient distribution (mainly spoilage), possibly avoidable losses to unsatisfied quality standards. The category "non-food use" refers to losses used for manufacture of non-food products (e.g. cosmetics, leather, fertilizer).

gle products can be much higher, especially for rare and perishable products with high fluctuations in demand.

In small shops the rate of unsold products tends to be higher, mainly because of lower sales volumes and higher fluctuations in demand. Nevertheless exceptions exist, e.g. in the analysed whole food shop, where most unsold products are donated or distributed to staff.

The analysis of the fruit and vegetable logistics centre of a major retailer shows that the losses between producer and retailer are relatively small for fresh fruits and vegetables. Between 0.35% and 0.44% of the delivered products are lost due to damages during transport and due to spoilage and unsatisfied quality standards. Compared to the losses in the stores (8–9%), they are of minor relevance. One reason for the small loss fraction is, however, that most substandard products are already sorted out earlier in the food value chain, i.e. in the agricultural sector.

For bread and pastries, the average losses are estimated at 3–7%, with an average of 5.1%. The results show that the losses are variable, depending on bakery size, location, strategy, and variety of products. One city bakery with between 20 and 30 branches estimated its losses in the major branches at 5%, in the smaller branches up to 20%, with average losses of 8%. Thereof, 1.6% are reused in their own production (e.g. as bread crumbs) and 0.4% are donated. The remaining 6% are fed to livestock. An old, traditional bakery with a narrow range of steady customers has kept its original philosophy not to overproduce. Most unsold products are consumed by the staff or reused. The losses fed to animals were roughly estimated at 1% of the volume of sales.

This data is coherent with estimations from two supermarkets, where the baked goods that are written off were in the same range. However, the rate of losses fed to animals has decreased since a new legislation was introduced in July 2011. In this analysis, it is assumed that 15–20% of the retail losses are used for biogas (based on BLW, 2010).

3.2.6. Losses in private households

Losses in households were estimated from a study conducted in the UK (Quested and Johnson, 2009). We assumed that Swiss households waste the same proportions as UK households in each food category. Considering the Swiss consumer basket and the average calorific content of each food category, 23% of the energy of the food purchased are wasted. From this, 16% is avoidable, 5% possibly avoidable, and 2% unavoidable. The food categories with the highest avoidable losses are bread and pastries, potatoes, unprocessed vegetables, apples, rice, and pasta (31–39%). A table with all the values is displayed in SI, Section 4.16. Overall, households produce 45% of all the avoidable losses across the food value chain (Fig. 3).

These food loss amounts are higher than the avoidable losses reported by Quested and Johnson (2009). This is mainly explainable with drink waste, which is included in the UK study, but not in this study. Moreover, the percentages in this study refer to the calorific content of the food, whereas Quested's numbers refer to mass.

However, the losses reported by Cofresco (2011) are significantly lower (12% of the food purchased, without unavoidable losses). A reason for the differences may be the method of data acquisition. Unpublished analysis by WRAP indicates that quantities of waste recorded in diaries are approximately 40% lower than those obtained from analysis of waste streams (Quested and Johnson, 2009).

3.2.7. Food donations

In Switzerland, most donations are organised by four institutions. In 2009, around 8000 t of food were donated. In the same year, the Swiss food consumption amounted to 5,400,000 t (SBV, 2009). Consequently, the food donations accounted for 0.15% of the mass of the food consumed at the retail level (consumption of households and the food service industry). There is a high potential to increase food donations (Tdd, 2011).

3.3. Comparison of food losses at the various stages of the food chain

As shown in Fig. 3, the largest contribution to food losses occurs in households and in processing with a waste share of more than 20% of their input. However, nearly two thirds of the losses in processing are unavoidable, while most of the losses in households are avoidable. The second largest contribution to the avoidable losses, relative to the input, is caused by the food service industry (13.5% of the food purchased). Nevertheless, the contribution to the total avoidable losses is only 5%, because food service outlets only consume 15% of the food, while 85% is consumed in households (SI, Section 2). The avoidable losses in agriculture account for 13%. This fraction is in reality higher than indicated here, since crops remaining unharvested are not included in this model due to lack of data.

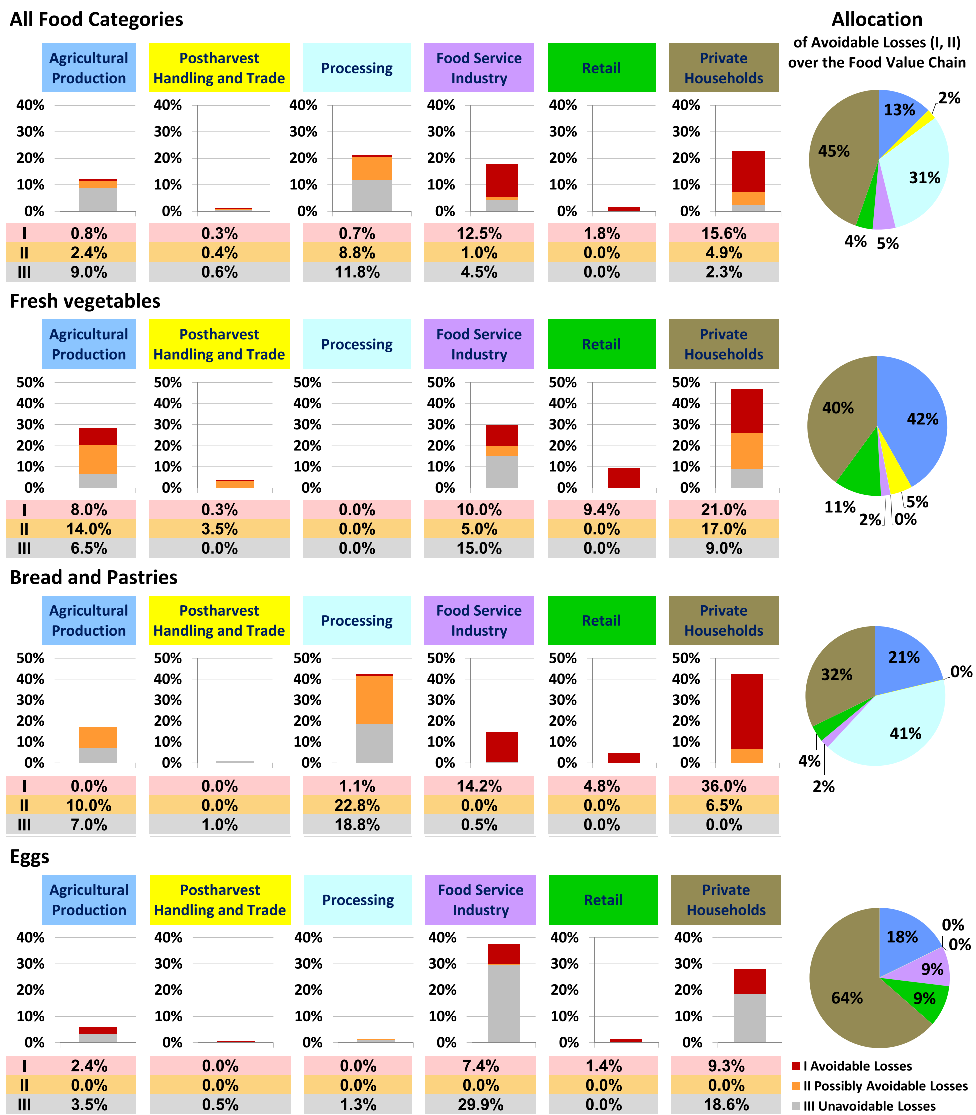

Fig. 3. Losses at each stage of the food value chain, in percentage of the food input into the corresponding stage. In the case of agriculture, the food input corresponds to the amount of edible food that could be harvested at harvest time. Grey are unavoidable food losses, orange possibly avoidable, and red avoidable losses. The results are shown for all food categories (graphs on the top) and for three characteristic food categories associated with relatively high loss rates (fresh vegetables, bread and pastries, and eggs). The pie charts on the right hand side show the relative contribution of the avoidable losses at each stage of the food value chain to the avoidable losses over the entire food value chain. All values refer to the calorific content of the food.

Retail and trade losses are low thanks to technological measures and a high level of organisation in Switzerland.

In the case of fresh vegetables, the avoidable losses in agriculture and households are much higher than the average losses for the other food categories. The main reason is the gap between supply and demand, which results from their unpredictability and from the high perishability of fresh vegetables. The latter is also the main reason why 38% of the edible parts purchased are thrown away by households.

Avoidable cereal losses in the food value chain of bread and pastries are primarily caused by quality sorting in mills and agriculture. Since most of the substandard breadstuff is fed to livestock, these losses are ecologically less relevant. In contrast, many of the losses at home and in restaurants are entirely lost.

In the case of eggs, households contribute 64% to the avoidable losses. However, the total losses are relatively low. This is typical for animal products, since they are generally more expensive. The avoidable losses in agriculture primarily result from meat of laying hens, which is in lower demand than poultry.

3.4. Total potential

Generally, there are two approaches to improve the efficiency of the food value chain with current best available technology. The first approach is an optimisation of the distribution system from the point of production to the consumer. The theoretical potential for increasing food availability with this measure is 25% relative to present food energy consumption. Secondly, 25% more calories could be saved for human intake if all the edible parts of the products were eaten and appropriate methods of cooking and preparation were adopted (e.g. recipes for bread from previous days). In total, with these measures, 50% more food calories could be available for consumption from the same agricultural land as today (Fig. 4).

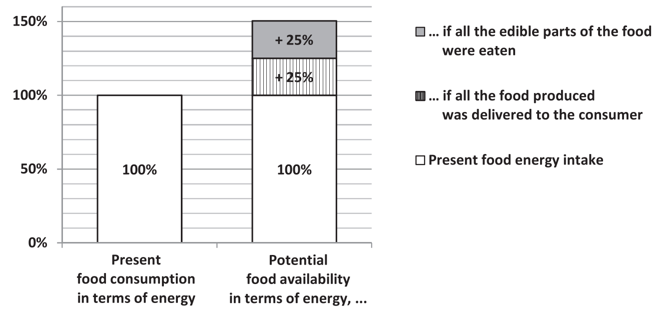

Fig. 4. Total potential of avoiding food losses in Switzerland (without technology improvement beyond current best available standard): in a theoretical scenario of perfect distribution and the use of all the edible parts of the food 150% of the presently consumed food calories would be available for consumption.

A third, long term approach to improve the efficiency of the food value chain is technology improvement and innovation. However, the corresponding potential of reducing food losses is not quantified in this paper.

3.5. Data reliability and uncertainty

The pedigree matrix for uncertainty estimation reveals uncertainty factors between 1.11 and 2.02 for the losses in different food categories and at different stages of the food value chain (Tables S9 and S10 in SI). The overall losses in retail are considered most reliable, followed by household losses and foodservice losses. The highest uncertainty is attributed to the losses of eggs, sugar, canned fruits, and cereal products at the stages of agricultural production, postharvest handling and trade, and processing. The losses in the processing industry are uncertain because they vary fundamentally between different products, methods of processing, and external factors. For example, the quality losses of cereals are very variable from year to year, depending on weather conditions and quality standards (SBV, 2011).

Household food losses have been analysed in several countries, but only the UK study is based on both a representative number of households and on measurements instead of only questionnaires (Pekcan et al., 2006; Quested and Johnson, 2009; Sibrián et al., 2006; Sonesson et al., 2005; Thönissen, 2009). According to Stuart (2009), consumers substantially underestimate their losses when self-reporting. Thus, there is a lack of reliable data about the variation of household food waste amounts in different European countries. However, there are significant disparities in food habits across European countries. For example, southern European populations generally consume greater amounts of cereals, fish and seafood, and fresh fruits and vegetables than the rest of Europe (Trichopoulou et al., 2002). These food categories are correlated with higher-than-average household losses, leading to the hypothesis that household food waste varies from country to country.

Furthermore, major data uncertainty lies in the losses in agricultural production (especially for fruits and vegetables), in the fishing industry, and in the processing sector. These sectors are very heterogeneous and therefore require extensive individual analyses for different food categories. The estimations of agricultural losses were based on five Swiss farmers' interviews and on values from literature, the latter referring to Europe. In the processing sector, the losses in cheese production, pasta production, bread baking, and vegetable and fruit processing were estimated and partially measured by six firms of the Swiss food industry. For the remaining food categories, the losses in processing were based on literature (details in Tables S9 and S10 in SI). However, more farms and processing companies should be analysed in order to get reliable results.

Loss data in the retail sector is relatively reliable. However, discount supermarkets are underrepresented in the current analysis and quantitative data from small retailers is lacking, even though they are assumed to be heterogeneous in terms of food losses. A more detailed analysis of discounters and of a representative number of small retailers would be desirable.

The food loss rates of imported products can differ substantially from those of Swiss products. Losses that were due to cross-boundary transport were considered in the present paper, as these were reported by the retailers and distributors, but not the losses that occurred at the production site. However, the differences in weather, climate, and soil mainly affect the unavoidable losses. The potential for the reduction of food losses is expected to depend mainly on the Swiss consumers' expectations and the retailers' quality standards that do not differ between imported and Swiss products. Nevertheless, in a future analysis the losses of imported products should be analysed separately.

The total avoidable losses estimated in this paper (299 kg/cap/a) are consistent with FAO's estimate of 280 kg/cap/a for Europe (Gustavsson et al., 2011). While these overall figures and the result that household losses make up the major part of the losses are rather robust, further studies are needed to further narrow down uncertainties for individual stages and food categories.

4. Conclusions and outlook

Roughly one third of the edible calories produced for Swiss consumption are lost over the whole food value chain. Thus, reducing food losses is an effective way to increase efficiency and reduce the environmental impact of food consumption.

The ecological relevance of food losses does not only depend on the amount, but also on the type of food, where in the food value chain it is lost, and how it is recycled or disposed of. For example, carrots remaining in the fields are ecologically less relevant than carrots wasted by households after being transported, stored, packaged, and processed. Cereals sorted out in mills and used for feeding are less relevant than the same amount of baked bread thrown to waste in a restaurant. Therefore, food losses should not only be quantified, but also evaluated by life cycle assessment. This would allow more accurate quantification of the environmental benefits of reducing food waste and help us define fields of priority.

However, measures to avoid food losses have to be taken at all stages of the food value chain. The implementation of measures requires all actors to be involved, including the government. This is particularly so because some food losses are not only caused in the stage where they arise. The consumers' expectations concerning aesthetic characteristics, freshness, remaining duration of storage, variety and availability cause many good products to be rejected (Teitscheid et al., 2012). For example, fruits and vegetables rejected in agricultural production are a consequence of cosmetic standards defined by the trade sector. These standards, in turn, are partly developed according to customers' preferences. Therefore, an effective reduction of food losses is often only possible if several actors collaborate. Food donations are another measure to reduce food losses and they are socially and ecologically highly beneficial. However, donations alone cannot solve the problem of food losses, mainly due to logistic, political, and hygienic limitations.

As already confirmed by previous studies (Quested and Johnson, 2009), households are the major source of food losses. Thus, consumer awareness, good planning, and correct storage of food are crucial. Since food loss amounts highly depend on agricultural infrastructure, food processing technologies, climatic conditions and income, the results of this analysis cannot be simply extrapolated to developing countries, but the methods used could be applied to these regions. However, for developed countries with similar climatic and economical conditions as Switzerland, the results of this analysis could be an indication for their scale of food losses.

More research is required to understand and solve the problem of food losses. This should not prevent us from taking immediate measures to avoid food losses already now. For example, even without a more detailed environmental assessment, it is clear that waste in the households is highly relevant and often unnecessary and, thus, should be reduced.

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We thank all organisations and contact people for delivering information.

Appendix A. Supplementary material

A pdf-file with supplementary data containing background information about data sources, calculations, and data quality can be found, in the online version, at http://dx.doi.org/10.1016/j.wasman.2012.11.007.

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