Food waste and resource efficiency

development and demonstration of a conceptual and methodological framework

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Food Waste and Resource efficiency – Development and demonstration of a conceptual and methodological framework

1. Introduction

The goal of this paper is to establish and demonstrate a methodological and conceptual framework for understanding the concepts of resource efficiency and food waste, including how the concepts can be made operational for measuring resource efficiency and food waste in Denmark. Some of the perspectives to this are to what extent economic resource waste is associated with food waste and food loss? And the potential size of the resource base for developing new approaches to recycling and utilisation of unused food products and by-products.

The paper and the underlying analysis has been prepared on request from the Danish AgriFish Agency, within the framework of the contract on commissioned work between the Department of Food and Resource Economics and the Danish Ministry of Food, Agriculture and Fisheries.

2. Definitions of food waste and resource efficiency

2.1 Food loss and food waste

Food loss is considered as loss of food which could have been eaten by humans. The most commonly used definition is:

> *"Food losses refer to the decrease in the edible food mass throughout the part of the supply chain that specifically leads to edible food for human consumption"* (Gustavsson et al., 2011)

A distinction can be made between food loss and food waste, where the distinction is mainly related to the nature of the loss and to its origin in the food supply chain. Not all food that is lost in the supply chain is fit for human consumption (Kantor et al., 1997). This should be considered when looking for solutions. Food losses in primary production and processing are mainly caused by inefficiencies in the food supply chains, such as poor infrastructure and logistics, lack of technology, insufficient skills, knowledge and management capacity of supply chain actors, and lack of access to markets. Losses can also occur at later stages once the food has left the manufacturer and is retailed, distributed and consumed. In this case the word used could be "waste" (Parfitt, 2010).

Under food waste in production and processing we can mention categories such as hidden food waste (waste of plants and animals) and unused products (used for purposes other than human consumption). This is waste that could have been used for human consumption, had they been treated or utilised optimally through the supply chain from production to retailer. The hidden waste could be in the form of raw materials or ingredients that were never used for final consumption. Specific examples include waste/losses in the field where as a result of disease there is harvested less grain than the maximum potential, or if the manufacturer must, for various reasons, apply their raw materials in a non-intended or non-optimal way. This could be grains which will only be an edible food when the grain is processed, or fruits and vegetables that have been left in the field as a result of a breach of contract, or finally animals that die of disease or are discarded at slaughter.

Unused products that are produced in addition to the main food product, but are not intended for human consumption, include slaughterhouse waste such as bones and blood. These parts are not suitable for human consumption and may therefore be characterised as not being food waste. It is appropriate to mention that such unused products normally are used for other purposes.

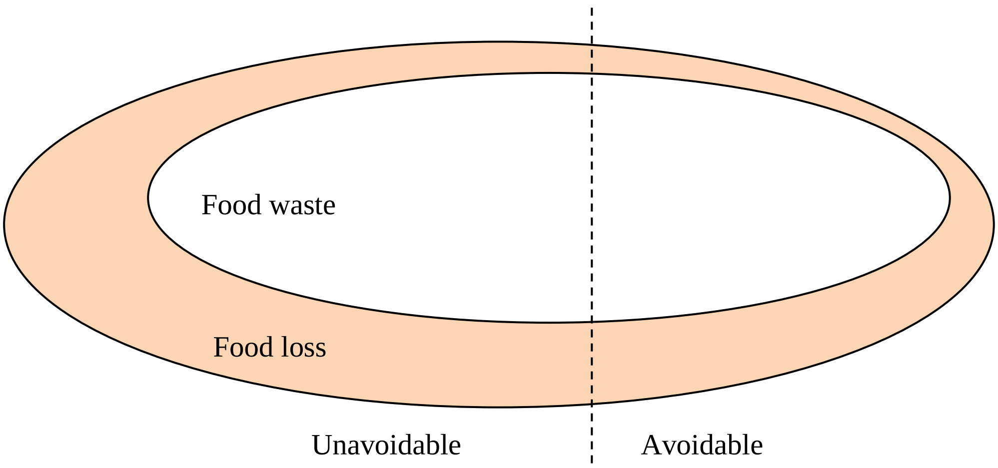

Figure 1. Avoidable and unavoidable food loss and food waste

Hence, one may distinguish between food loss and food waste – the former being more comprehensive than the latter – and between avoidable and unavoidable loss or waste, cf. Figure 1. Products become more valuable, with more resources (labour, capital, energy, etc.) embedded in them, the higher the location in the value chain, i.e. the closer to final consumption, cf. Figure 2. This implies that the resource waste associated with food waste would tend to be relatively larger than that associated with food loss, of which a considerable share consists of relatively unprocessed products or by-products. Resource efficiency relates to the share of food loss or food waste that could be avoided.

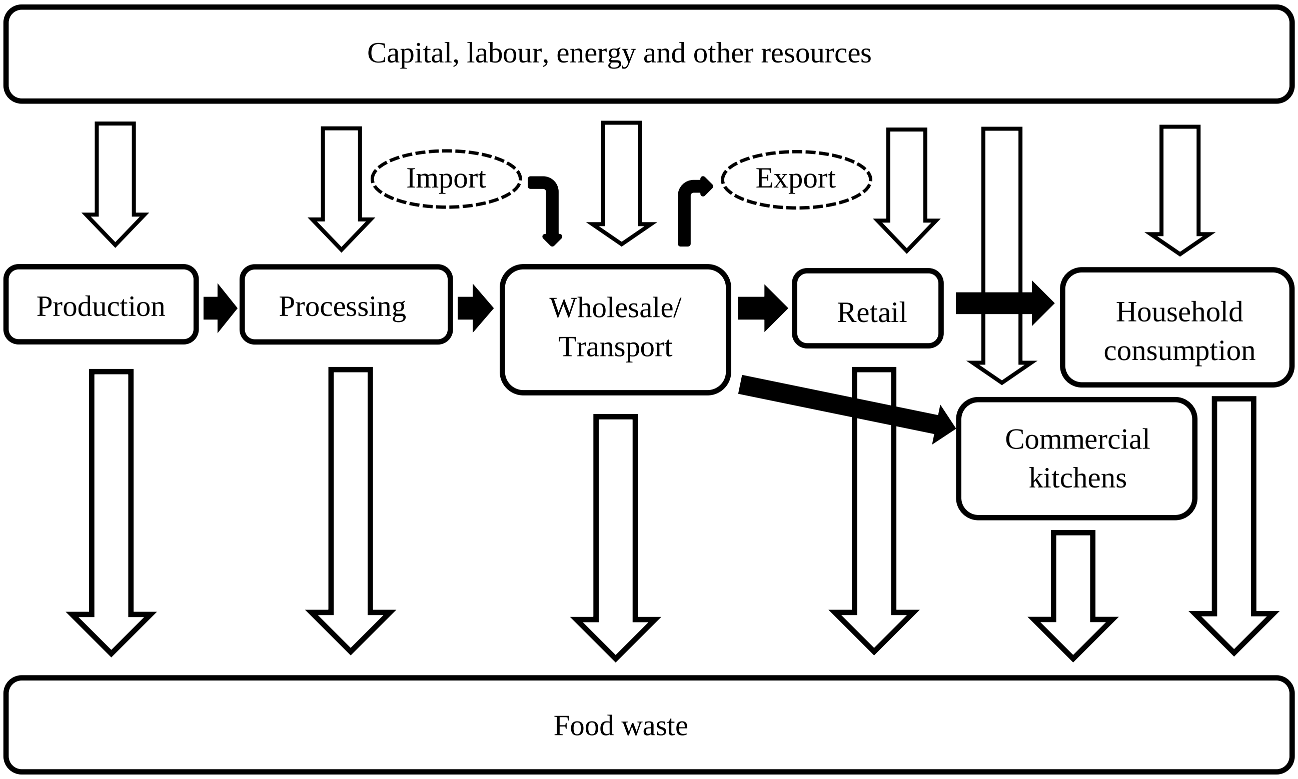

Figure 2. Food waste in the supply chain

The majority of the production from the primary sector is processed domestically (although there is an increasing trend towards international trade in raw materials directly from primary agriculture) and transported and distributed from there to the relevant markets domestically as well as abroad. Imported and domestic parts of food production are channelled to end-users both via retailers and via commercial kitchens. It is these commercial kitchens along with households where the majority of food waste in the latter stages of the supply chain occurs (Jensen, 2011).

2.2 Resource efficiency

Resource efficiency is a measure of the extent to which raw material resources of a commodity are used optimally. The problem is analogous to the measurement of productivity and efficiency in production, where for example it is investigated, whether labour and capital inputs are used optimally in production. The problem can be illustrated by the following isoquant diagram from standard production economics:

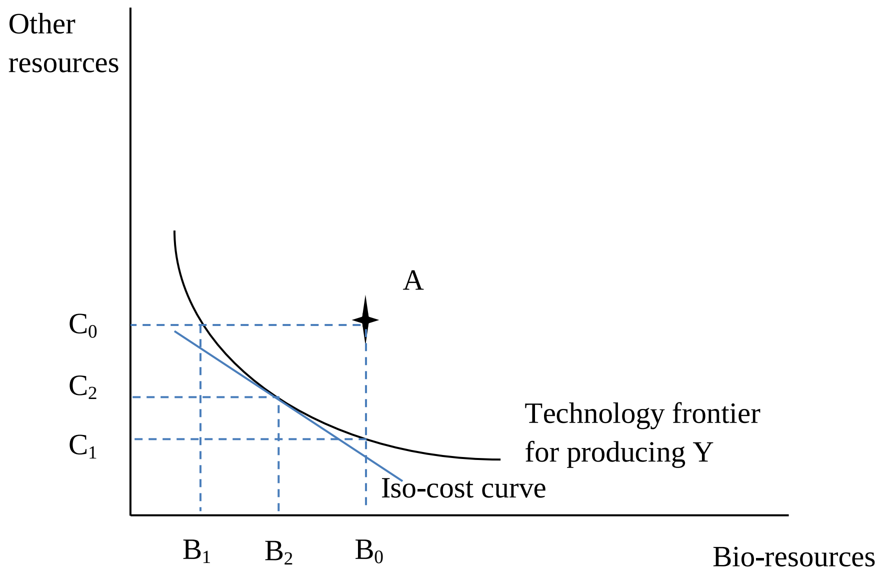

Figure 3. Isoquant diagram

Assume that an enterprise produces the output quantity Y, using the combination of bio-resources at the amount (B_0) and other resources at the amount (C_0), as represented by the point A in the diagram. But assume also that the same amount could be produced using smaller amounts of these inputs, represented by the technology frontier (isoquant) for producing Y. In this case, the utilisation of resources on this enterprise is not fully efficient. The degree of inefficiency is represented in the diagram as the "distance" between the point A and the technology frontier.

There is a vast literature on the measurement of such inefficiencies, suggesting alternative approaches to measuring this distance.

One approach would be to determine, how much the input of bio-resources could be reduced in order to obtain the same level of output, provided that the input of other resources was kept unchanged. Such an approach is represented by the difference between B_0 and B_1 in the diagram. Or alternatively, to determine how much the input of other resources could be reduced, while maintaining the input of bio-resources and the total output level, represented by the difference between C_0 and C_1 in the diagram. Such measurements could be considered as partial efficiency (or productivity) measures, and labour productivity is a common example of such partial measures, but the measure could be equally relevant with regard to bio-resources, e.g. number of pigs entering slaughterhouses, or amount of feed used in pig production.

But these partial "benchmarks" do not take into account the overall optimisation of the production activity, which involves the composition of inputs derived from price relations between the inputs. Therefore, these benchmarks will rarely represent an economic optimum for the enterprise – and hence not represent a relevant point of comparison. Instead, the point (B_2,C_2), where the marginal technical rate of substitution equals the relative prices, represents an optimum (and a relevant point of reference), and from a more 'holistic' perspective, resource use efficiency is represented by the distance between A (B_0,C_0) and the point (B_2,C_2). This approach is consistent with a 'total factor productivity' measure (cf. below).

3. Review of literature on measuring resource efficiency and food waste

3.1 Studies on food waste

Accurate data about food waste is often lacking as it is difficult to determine the precise amount of waste occurring due to measurement issues and a reluctance of stakeholders in the food industry to release results which can damage their image. This section gives a brief overview of the few studies that have been conducted regarding quantifying food loss and food waste.

Lundqvist et al. (2008) estimates that waste corresponds to almost half of all food before it reaches the consumer. They arrive at this estimate by looking at the average amount of food produced globally at the field level taken from Smil (2000) and then use estimates from Kader (2005) for losses, conversions (conversion of food in terms of grains used for feed to produce animal food) and wastage in the food chain.

Gustavsson et al. (2011) estimates 30-50% of food in the world is lost or wasted across the food chain and is never consumed by humans. For various commodity groups they made use of a mass flows model to account for food losses and waste in each stage of the supply chain. They quantified the food produced for human consumption by using allocation factors to determine what is produced for human consumption and not for animal feed. Then they looked at each stage of the food supply chain and estimated losses and waste using FAO's Food Balance Sheets[1] and literature on global food waste as well as their own assumptions.

FAO (2013) also used Food Balance Sheets to gather data regarding global mass flows of food for various regions and agricultural sub-commodities. This gives the total amount of food available for human consumption during one year. Then wastage percentages from Gustavsson et al. (2011) are applied to the data to quantify food waste volumes for each studied region, commodity and at each phase of the supply chain. The study also calculates volumes for edible and non-edible food, but only estimates food waste for edible part of food.

Gunders (2012) estimates that 40% of food goes to waste in the US. They also identify food losses at every stage in the supply chain. They separate commodity groups into grain products, seafood, fruits and vegetables, meat and milk. Another study investigating food waste in the US is Kantor et al. (1997), who make a distinction between "not recoverable" and "recoverable" food for human consumption. They estimate food loss by applying loss factors in various stages of the supply chain, to the amount of food available for human consumption. However, "pre-harvest, on-the-farm and farm-to-field" losses were not measured, but in estimating the food available for human

[1] http://faostat.fao.org.

consumption they did remove inedible food parts based on the USDA Economic Research Service conversion factors[2]. These factors account for processing, trimming, and other weight reductions that occur as raw agricultural commodities are made into semi-processed and final food products available for consumption at the retail, household, and foodservice levels.

In the UK, studies include Quested and Johnson (2009) and Ventour (2008), where the latter reported that around a third of purchased food is wasted by households, where 60% of this food can still be considered good for human consumption. The study interviewed numerous households to get an indication of the types of food the households waste, their attitudes, socio-demographics and disposal options. Included in the study was also a physical analysis of the contents of trash bins. Based on the sample households, the study estimated the annual weight of food waste collected from the homes. Quested and Johnson (2009) also did not cover non-household sources of waste in the food supply chain, but does categorise the food and drink waste by how avoidable the waste was as well as the reason for disposal. They present three categories: Avoidable, possibly avoidable and unavoidable. The study estimated the cost by assuming the waste is equal to the retail price of the products wasted, which is then only applied to the avoidable part of the waste.

In Holland, the Dutch ministry of food has also investigated the extent of food waste in their country (Ministry of Agriculture, Nature and Food Quality, 2010). The short report quotes food waste percentages and costs obtained from Milieu Centraal[3] for the amount of food that is lost in production, industry and trade as well as in the retail and “out-of-home” market. They also estimate how much edible food Dutch consumers throw away.

Parfitt et al. (2010) review international literature on food waste in the supply chain and conclude that there is a lot of variation in data used and estimates made. They present post-harvest weight losses from various sources for rice, grain, fresh fruit and vegetables mainly for developing countries, but also for the UK and USA. Household food waste estimates are also presented where the studies above from WRAP are referenced. The paper ends with some projections for future trends in food waste, emphasising the importance of implementing sustainable solutions across the entire food supply chain to realise the potential for food waste reduction.

Turning to Danish studies regarding food waste, Kjær and Werge (2010) in a data and knowledge overview report, state that data availability for food waste in the Danish food market and industry is lacking and in some cases up to 20 years old. They identify five main actors in the food chain: food processors, wholesalers, retailers, commercial and institutional kitchens, and households. The study does not include primary agriculture producers. The report also draws on non-Danish studies which are also mentioned above, to suggest that there is a potential to prevent the generation of avoidable food waste.

[2] http://www.usda.gov
[3] http://www.milieucentraal.nl

Mogensen et al. (2011) estimated that about 303,000 tons of edible food is wasted along the food supply chain at the levels of production, manufacturing and retail. Focus is placed on the stages of the supply chain from production in agriculture and horticulture (fishery is excluded), processing, transport and wholesale to both commercial kitchens and retailers. In their report they also differentiate between food waste which is hidden and bi-products which are not suitable for human consumption. Data is collected from some of the previous literature mentioned above for various food sectors on the amount of resource input usage and the amount of output. Similar to Kjær and Werge (2010) the study concludes that there is a need for updated Danish data for the amount of food loss and waste from all stages of the food supply chain.

Jensen (2011) performs an economic analysis of the value of edible food loss in the food supply chain for various food categories and estimates the economic value to be 6.7 billion DKK annually, where the majority of the economic loss is attributed to households. The study also shows that the economic value of hidden food waste is expected to be more moderate when compared to edible food waste and that the value of unused bi-products is similar to that of hidden food waste. Jensen (2011) also notes that there should always be expected a certain amount of food waste which may be almost unavoidable and that the question is whether it is better to attempt to eliminate this waste or to increase efficiency instead.

Recently DEPA (2012) estimated that about 105 kilos of edible food was wasted by the average Danish household, which is about 23% of the total domestic waste. Similar to Ventour (2008) and Quested and Johnson (2009), the study only includes household waste, where phone interviews were used to obtain households willing to have their waste collected to determine the composition and also to obtain attitudinal information.

3.1 Studies on resource efficiency

Similar to food waste, there is a lack of studies conducted on resource efficiency in the food chain. This section gives a brief review of existing studies

Kummu et al. (2012) begins by calculating food losses in the chain in terms of weight and food supply (kcal) and then calculated the resources used (water, land, fertilisers) to produce the losses. Finally they estimate the potential saving of food supply and related resources that could be made through a more efficient food supply chain. Losses were estimated using loss percentages from Gustavsson et al. (2011) and FAO Balance Sheets. Once the losses were calculated in terms of weight, this was converted into food supply (kcal) by using conversion factors again based on FAO Balance Sheets. To calculate the water, land and fertiliser used to produce the food supply chain losses, they used the total domestic food supply quantities minus exports and generated a minimum loss scenario. This scenario was said to estimate how the use of resources on food supply chain losses could potentially be reduced compared to the current situation.

BIO Intelligence Service (2012) attempts to establish which grocery products are likely to contribute most to environmental impacts associated with UK household consumption, in terms of greenhouse gas emissions, material use and waste as well as water and energy usage. The information presented in the report comes from previous studies. The assessments of the grocery products combine data on sales (kg) with data on the life-cycle carbon, water and energy footprint for the products (kg CO_2e/kg, litres/kg and MJ/kg, respectively). The grocery products include drinks, cereals, canned and frozen food, bakery products, dairy, meat, fruits and vegetables.

Fisher et al. (2013) is another assessment of the resource use and environmental impact of grocery products and looks for possible gains in resource efficiency. Their main conclusion is that system-level innovation could provide the greatest benefits such as shifts in dietary patterns, avoiding waste and closing of resource cycles. Their approach contains a quantification of resource flows and environmental impacts of the EU food cycle in terms of volumes of food produced, processed, imported, exported, consumed and wasted as well as the inputs and emissions to and from the system. They obtain their data on flows of commodities and nutrition from FAOSTAT and Eurostat and data for resource use and emissions from previous studies.

Henningsson et al. (2004) looks at the economic value of resource efficiency by focusing on waste minimisation, stating that the greatest potential for financial savings was in the reduction in the use of raw materials. They identify minimisation of food packaging, reducing electricity and water consumption, and improving effluent quality as sources of substantial savings. The discussion section of the paper also mentions alternative uses of by-products of food production, stating that they are often of high enough quality to be sold on for use in second grade food products such as in fast food, soups or baby food. They also comment that other approaches for using food and drink production wastes are required, such as applications in natural products like toiletries or cosmetics.

European Commission (2011) deals with general resource efficiency across Europe and outlines a series of milestones and indicators for measuring progress in improving resource efficiency, where the most important of these is the so-called ‘Resource Productivity’ used to measure an improvement in economic performance while reducing pressure on natural resources. Their focus is mainly on proposing incentives for investments in efficiency to stimulate investments in resource efficient production methods as well as changing consumption patterns to greener products and recycled products. In relation to food, the report merely states that there is required a combined effort by farmers, the food industry, retailers and consumers through resource-efficient production techniques, suitable food choices and reduced food waste in order to improve resource efficient and food security at a global level.

Robinson and Lee (2011) conducted a series of site reviews of companies to assess the food and packaging waste generated for various subgroups of food and drink including frozen foods, ready meals, prepared sandwiches and sweets. The areas of focus were stocks, spillage allowances, raw material packaging and waste management. A Pareto approach to analyse the data from the companies was used to identify opportunities for reducing waste and improving efficiency leading to returns to the business.

4. Quantifying resource efficiency and food waste in this report

In the following, we will assess two components of "hidden" food loss in Denmark quantitatively: food loss in terms of inefficient utilization of bio-resources in primary production, and food loss in terms of sub-optimal use of agricultural and fisheries products in further processing and distribution. Furthermore, the project delimits itself to main lines of food production: grain- and grain-based food products, milk and dairy products, meat products, horticultural products and fish/seafood products.

In order to quantify food waste, we make use of data specifically established for the purpose by Kristensen et al. (2014) and Cold et al. (2014), as well as quantitative results from previous reports and welfare economic prices determined on the basis of national data, including agricultural statistics from Statistics Denmark.

4.1 Data sources

In relation to **resource efficiency in the sense of reaching the output potentials** from scarce resources in primary production, data on product yields, inputs and partial input-output ratios (e.g. crop yield per hectare, milk yield per cow, piglets per sow, crop yield per kg nitrogen, feed conversion rates etc.) can be useful for partial productivity or efficiency assessment, corresponding to the distance between B_0 and B_1 in Figure 3 above.

Economic Accounts for Agriculture constitutes another data source for assessment of waste and resource efficiency in agricultural production. Economic accounts measure output and inputs in economic (value) terms, and combined with price information, such information can be utilised to assess resource efficiency comparatively – across farm types, across countries and over time, using productivity measures as those presented above (i.e. Total Factor Productivity or Partial Factor Productivity measures). Economic Accounts for Agriculture are procured both at a national level (Agricultural Gross Factor Income statistics), as well as at the farm level (Farm Accountancy Data Network – FADN). For Denmark, both statistics are produced by Statistics Denmark, following coordinated standards agreed in Eurostat, including a farm typology for FADN data.

Examples of such data for cereals production for the period 1990-2012 are given in table 1.

Table 1. Cereal production - efficiency data per hectare

	1990	1995	2000	2005	2010	2012
Feed units per hectare	5944	6180	6098	6024	5809	6141
Nitrogen harvested, kg/ha	107	106	96	95	88	89
N-efficiency[1)]	0,82	0,81	0,81	0,75	0,76	0,79
	1991/92	1995/96	2000	2004	2010	2012
Fertilizer cost	1114	1030	874	1030	741	986
Other variable costs	1804	1684	1831	2133	2392	3017
Labour cost	1753	2062	1607	1630	1828	1804
Capital cost	2316	2226	2659	2816	2574	2894
Price – energy (1990=100)	100	88	137	181	218	272
Price - labour (1990=100)	100	116	140	167	198	207
Price - capital (1990=100)	100	59	64	38	15	10

1) Share of applied nitrogen, which is harvested again - assuming fertilization according to quota

Source: Kristensen et al. (2014), Statistics Denmark (various issues)

The upper part of the table represents physical indicators of production efficiency (Kristensen et al., 2014). N-efficiency represents the share of nitrogen application (maximum allowed application according to Danish nitrogen regulation) that is harvested in the crop. The bottom part of the table originates from farm accounts statistics for individual lines of agricultural production (Statistics Denmark, various issues). Because this statistic was not produced for the calendar years 1990, 1995 and 2005, we approximate these years by data from the crop years 1991/92, 1995/96 and the calendar year 2004. Whereas the physical indicators in the upper part of the table are suitable for assessing partial aspects of resource efficiency at a relatively detailed level, the economic indicators in the lower part of the table are suitable for assessing more holistic economic aspects of economic efficiency, however at a less detailed level, in agricultural production.

In order to operationalize the analysis in relation to **food waste and efficiency in the use of food resources**, it is useful to consider supply balance sheets for the respective commodity categories (Figure 4).

Primary sector stage
Supply
Beginning stock
Production
Imports
Use
Internal use
Domestic (primary) processing
Domestic (secondary) processing
Exports
Loss
Ending stock

Processing stage
Supply
Beginning stock
Domestic raw materials
Imported raw materials
Use
Internal use
Primary processing for domestic market
Secondary processing for domestic market
Export
Loss
Ending stock

Figure 4. Supply balance sheets for primary production and processing stages

For example, in primary grain production, the total supply within a given year consists of the production within the year, imports of grains to the farm sector during the year, plus the beginning stock of grain at the farm level. This total supply is allocated to a number of uses within the same year, including internal use (e.g. for feeding, seeds, etc.), sales to the domestic processing sector (which may be distinguished in primary processing aiming at the "main" products, and secondary processing making use of by-products, etc.), exports, ending stock and losses.

Supply balance data are procured by for example Statistics Denmark and Eurostat for some of the agricultural supply chains. As an example, Table 2 shows the Danish supply balance for grains in 2011.

Table 2. Danish supply balance for grains, 2011

	mill. kg
Total grain yield (2010)	8748
Net harvest (2010)	8530
Imports	605
Beginning stock	6478
Total supply	**15613**
Seed	283
Export	2038
Milling, flour, flakes, etc.	436
Industrial purposes	321
Ending stock	5840
Feed	6695
Total use	**15613**

Source: www.statistikbanken.dk

The construction of the supply balance sheets is based on information on physical quantities from a range of sources, including production statistics and trade statistics. However, most of the published statistics do not distinguish between different stages of the chains, although some information about the split between the stages can be discerned from the balances in some cases. And unfortunately, the most of the published statistics do not provide specific information about "Loss" in the balance sheet. In the grain example in Table 2, losses in connection with harvesting (about 2.5%) are deducted from the total harvest, hence the term "net harvest". And losses associated with the different uses of grain are embedded in the figures for these respective uses.

Whereas economic accounts data and food supply balance sheets tend to be the most relevant generally available data for analysing resource efficiency and waste in the food supply chains (after primary production), it should be noted that these data are generally not collected and published for this purpose. However, some of the uses in the supply chain may be considered as more valuable than others, and the fraction of production directed to relatively low-value use could be interpreted as an indication of inefficiency in resource use. It should however be noted that such interpretations are subject to some uncertainty.

More precise estimates of food losses within the supply balance framework hence would require more information about the food losses associated with different uses of the products. Hence, existing data sources tend to be deficient, when it comes to evaluation of resource efficiency in the food supply chains. Better data would be desirable with respect to losses in primary production (harvest, livestock mortality, etc.), and with respect to the level of detail in the categorization of uses of these products, for example in different categories of potential value-added in the supply chain. Furthermore, there would be a need for more systematic collection of data on waste from different stages of the supply chain.

4.2 Measures of food loss, food waste and resource efficiency

Using the theoretical framework illustrated in Figure 3, different measures of food loss, food waste and resource efficiency can be defined, of which some are expressed in absolute (tonnage) terms, reflecting the physical amounts of food waste or underutilised resources to be dealt with, and others expressed in relative (percentage) terms, reflecting the degree of under-utilisation and room for improvement. In primary production, we interpret "food loss" etc. as loss of bio-resources (fertilizers or feed) in production. Regarding **food loss and food waste**, two absolute measures can be considered:

$$Absolute\ technical\ food\ loss = B_0 - B_1$$

$$Absolute\ food\ waste = \alpha \cdot (B_0 - B_1)\ , \qquad \alpha \leq 1$$

The absolute technical food loss measures the excessive use of the bio-resource to produce output Y, given the input of all other inputs, and hence the amount that could potentially be saved or used for other purposes. Absolute food waste is the fraction of total food loss that ends as food waste, represented by the share α, and this amount could be considered as the most "easy to collect and use" for e.g. energy production, bio-refining, etc. For the "hidden" food loss in primary production, α is assumed to be close to zero.

$$Rate\ of\ technical\ food\ loss = \frac{B_0 - B_1}{B_0}$$

$$Rate\ of\ economic\ food\ loss = \frac{B_0 - B_2}{B_0}$$

By dividing the amount of technical food loss with the total amount of bio-resource used, the rate of technical food loss is obtained. This measure would represent the maximum technical extent to which food loss could be reduced while maintaining the same output and the same amounts of other inputs. However, taking into account the fact that such a solution will not be economically optimal, because it requires additional capacity costs to enhance the utilisation of the bio-resource, the economically feasible reduction of food loss can be represented by the rate of economic food loss (cf. figure 3).

The *rate of technical food loss* represents the share of bio-resources not fully utilised, when all other inputs are assumed unchanged. The measure requires data on actual use of the bio-resource in production (e.g. total number of pigs, total grain on the field) as well as data/estimates on the minimum amount of the bio-resource to produce the same amount of output, without changing the input of capital, labour, energy etc. Data could be measured in physical quantities or in monetary terms.

The *rate of economic food loss* represents the amount of bio-resources not fully utilised, when economic adjustments to undertake improved utilisation are taken into account. From an economic perspective, the measure is theoretically superior to the technical food loss, because it takes into account producers' propensity to change the composition of inputs, if utilisation of resources should be improved. On the other hand, the measure requires data on the substitution between bio-resources and other resources, which in turn requires specific assumption about the production technology (for example functional form and technical parameters of the technology). Econometric analysis on the basis of economic accounts data could be a way to solve this challenge. The measure can be calculated on the basis of physical quantity data or monetary cost data.

Two relative measures of **resource efficiency** can be derived from the theoretical framework in Figure 3 (note that the measures are defined relative to the observed resource use, not the optimal use):

$$Partial\ rate\ of\ bio-resource\ efficiency = 1 - \frac{w_B(B_0 - B_1)}{w_B B_0} = 1 - \frac{B_0 - B_1}{B_0}$$

$$Aggregate\ rate\ of\ resource\ efficiency = 1 - \frac{w_B(B_0 - B_2) + w_c(C_0 - C_2)}{w_B B_0 + w_C C_0}$$

Both resource efficiency measures are formulated as relative (percentage) terms. One challenge with some of these measures of food loss and resource efficiency is the fact that the technology frontier (comprising the points B_1,C_0 and B_2,C_2) is normally not observable, and attempts to measure efficiency measures based on these will have to build on further assumptions and estimates, cf. below.

Partial resource efficiency represents the degree, to which the bio-resources are utilised to a maximum extent. As this measure (in percentage) is calculated as one minus the technical food loss, this measure mirrors the technical food loss above.

Aggregate resource efficiency represents the degree, to which all resources (including bio-resources, capital, energy, etc.) are utilised to an optimal extent. As with the economic food loss measure, this measure is theoretically superior to the partial resource efficiency measure, but is faced with the challenge that an estimate of the optimal point is needed – an estimate which has to build on supplementary assumptions.

Assessment of the **development in resource efficiency over time** can be evaluated by means of productivity measures. The general literature on measurement of productivity growth distinguishes between total factor productivity and partial productivity measures.

Total factor productivity (TFP) is normally used to describe the relationship between a quantitative expression of the production and the usage of production factors, and TFP can be defined as follows:

$$Total\ factor\ productivity = \frac{Quantitative\ index\ for\ production}{Quantitative\ index\ for\ usage\ of\ production\ factors}$$

As is apparent from the formula of TFP, productivity growth happens when there is a greater amount of production using the same amount of production factors[4]. Alternatively, growth occurs when the same amount of output is produced using fewer inputs. Growth in total factor productivity is synonymous with a smaller total usage of inputs per unit, which is why growth in TFP helps to reduce unit costs. For example, a 2 per cent growth of TFP leads to a reduction in unit costs at constant factor prices of just under 2 per cent ((1 / 1.02 - 1) * 100 = -1.96 per cent).

Bio-resources productivity (BP) – like TFP – is defined based on production. It is the ratio between output and bio-resources usage (and is hence an analogue to e.g. labour productivity). The definition is as follows:

[4] The growth measured by the formula for TFP is only accurate when productivity is measured by the so-called Divisia index. If a different index is used, the relationship will only be an approximation.

$$Bio - resources\ productivity = \frac{Quantitative\ index\ for\ production}{Quantitative\ index\ for\ usage\ of\ bio - resources}$$

BP is generally greater than the growth in TFP in most industries, because the usage of bio-resources commonly grows less – or falls more – than the total factor usage due to a tendency to substitute bio-resources with tangible production factors. This substitution is partly because technological progress often saves on bio-resources. Other partial productivity measures similar to the BP could be imagined, for example partial productivity with respect to energy, land use or fertilisers.

These productivity measures are useful for comparative analyses, for example over time. Hence, given quantity indices for output and for bio-resource input or aggregate input over time, the measures can be used to evaluate the growth in BP or TFP. Often, such productivity measures are calculated on the basis of economic accounts data, where quantity indices are obtained by deflating value figures by price indices of the respective aggregates, for example total output value of agricultural output divided by a price index for total agricultural output. The calculation of such productivity indices can also incorporate the value of by-products in the output quantity index, and hence take into account the resource efficiency aspects related to the utilisation of such by-products. However, in cases of quality developments over time, for example where technological change opens up for new and highly valued by-products on the output side, this procedure involves a risk of under-estimating the real output growth, and in such cases there is a need for corrective actions.

In the quantitative analysis on primary agriculture below, we will focus on rates of technical and economic food loss and on partial and aggregate rates of bio-resource efficiency.

As mentioned, one challenge with these measures of resource efficiency is the fact that the technology frontier is normally not observable. Box 1 offers an approximate way to overcome this challenge, given a set of relatively few assumptions.

Assume that the frontier of the production technology can be described by a two-factor CES production function

$$\left(\frac{Y}{\overline{Y}}\right) = \left(\alpha \cdot \left(\frac{B}{\overline{B}}\right)^{\frac{\sigma-1}{\sigma}} + (1-\alpha)\cdot\left(\frac{C}{\overline{C}}\right)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}$$

Where σ is the (known) elasticity of substitution between the two inputs B (raw materials, e.g. nitrogen fertilizer or feed) and C (an aggregate of all other inputs: capital, land, labour, energy, etc.). Assume further that technological insight provides one observation on the technology frontier (e.g., lowest possible input of raw material B_1 to obtain output Y, given all other inputs C_0). Given this point, and the elasticity of substitution σ, it is possible to calibrate the parameter α as

$$\alpha = \frac{w_B / w_C}{(C_0 / B_0)^{\frac{1}{\sigma}} + w_B / w_C}$$

Utilizing the first-order conditions for profit maximization ($\partial Y/\partial B = w_B / p, \partial Y/\partial C = w_C / p$, where p, w_B, w_C are prices of output and the respective inputs), we can solve the following two equations to estimate the profit maximizing combination of B and C, as

$$B_2 = (1 + \dot{y} - (1 - s_b)\cdot \sigma \cdot (\dot{w}_b - \dot{w}_c))\cdot \overline{B}$$

$$C_2 = (1 + \dot{y} + s_b \cdot \sigma \cdot (\dot{w}_b - \dot{w}_c))\cdot \overline{C}$$

$$B_1 = \left(\left(\frac{B_2}{\overline{B}}\right)^{\frac{\sigma-1}{\sigma}} + \frac{1-\alpha}{\alpha}\cdot\left(\left(\frac{C_2}{\overline{C}}\right)^{\frac{\sigma-1}{\sigma}} - \left(\frac{C_0}{\overline{C}}\right)^{\frac{\sigma-1}{\sigma}}\right)\right)^{\frac{\sigma}{\sigma-1}} \cdot \frac{Y}{\overline{Y}} \cdot \overline{B}$$

Where $\dot{y}$ represents variable y's relative deviation from its mean value, etc.
Given these estimated optimal combinations of inputs, we can calculate the above measures of resource efficiency.

Box 1. Estimation of optimal resource use applying a CES technology assumption

In order to conduct quantitative analyses of resource efficiency within the framework in Box 1, it is necessary to calibrate the model, i.e. determine parameter values for the production functions for cereals, roughage, pigs and dairy cows.

First, based on the variation in farm accounts data during the period from 1995 to 2012, we estimate the elasticity of substitution, σ, between raw material (fertilizer or feed) and other inputs.

Second, assuming that the average of the observations 1990, 2000, 2005, 2010 and 2012 constitutes the point of calibration (i.e. the combination ($\overline{B}, \overline{C}, \overline{w}_B, \overline{w}_C$), we estimate the parameter α according to the expression in Box 1.

Third, we estimate the potential (maximum) output $\overline{Y}$ in the point of calibration by adjusting observed yield by TFP-inefficiency coefficients estimated by Rasmussen (2010) for crop farms (1,385*0,82*0,78=0,89), pig farms (1,193*0,9*0,88=0,94) and cattle farms (1,26*0,88*0,89=0,99), respectively. Furthermore, we assume an annual rate of technological (e.g. genetic) productivity growth of 0,5% in all sectors. Calibrated parameters are summarized in table 3.

Table 3. Calibrated parameters

	Cereals	Roughage	Pigs	Milk
Elasticity of substitution (fertilizer, other input)	0,4	0,4		
Elasticity of substitution (feed, other input)			0,3	0,6
Alpha	0,514	0,057	0,428	0,389
TFP efficiency	0,886	0,987	0,945	0,987
Technological growth	0,005	0,005	0,005	0,005

Using the calibrated parameters and the data, we can use the above formulae to derive the efficiency measures outlined above. Figure 5 shows the development in the rate of technical and economic bio-resource loss in cereals, roughage, pig and milk production. For cereals and roughage, bio-resource is represented by nitrogen input, and for pigs and cattle, feed input constitutes the bio-resource considered. Dashed curves represent technical bio-resource loss (i.e. relative deviation from technically feasible minimum use, B_0-B_1) and full-drawn curves representing economic bio-resource loss (i.e. relative deviation from economically efficient minimum use, B_0-B_2).

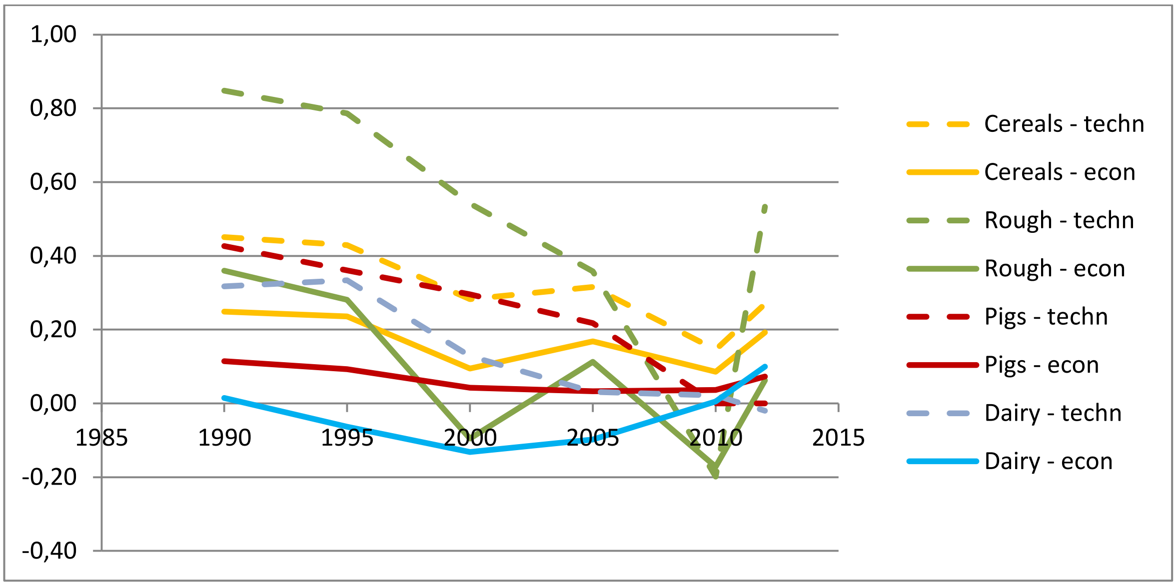

Figure 5. Technical and economic bio-resource waste in cereals, roughage, pigs and dairy cattle.

For all four types of agricultural production, technical bio-resource loss has been considerably larger than economic bio-resource loss, as expected from Figure 3, in the beginning of the period. Hence, although the waste of bio-resources could be reduced significantly (about 30-50% in the

1990's) from a technical point of view, parts of such reduction would be at the expense of lower efficiency in the use of other resources (e.g. labour, energy, capital, land) and hence the extent of waste reduction that makes sense from an economic perspective would have been lower (10-25%). However, according to the figure, the rates of both technical and economic bio-resource waste have been decreasing over time, and are now close to zero.

It should be noted that the model outlined in Box 1 constitutes a relatively simplified description of the production technologies in the respective agricultural sub-sectors over a time span of 22 years. Hence, some uncertainty in the calculations is unavoidable. This implies that in a few cases the model predicts B_1- and B_2-values that exceed the observed levels of bio-resource input – which in turn would imply that bio-resource losses were negative. This is especially the case for some of the most recent years in cattle and roughage production, which – as mentioned above – is calibrated to exhibit a TFP-efficiency close to unity, based on findings by Rasmussen (2010). In such cases, negative bio-resource waste rates should be interpreted as zeros.

Rates of partial bio-resource productivity and total factor productivity growth are other ways of representing the development in efficiency in the use of bio-resources. Such productivity measures are shown in Figure 6.

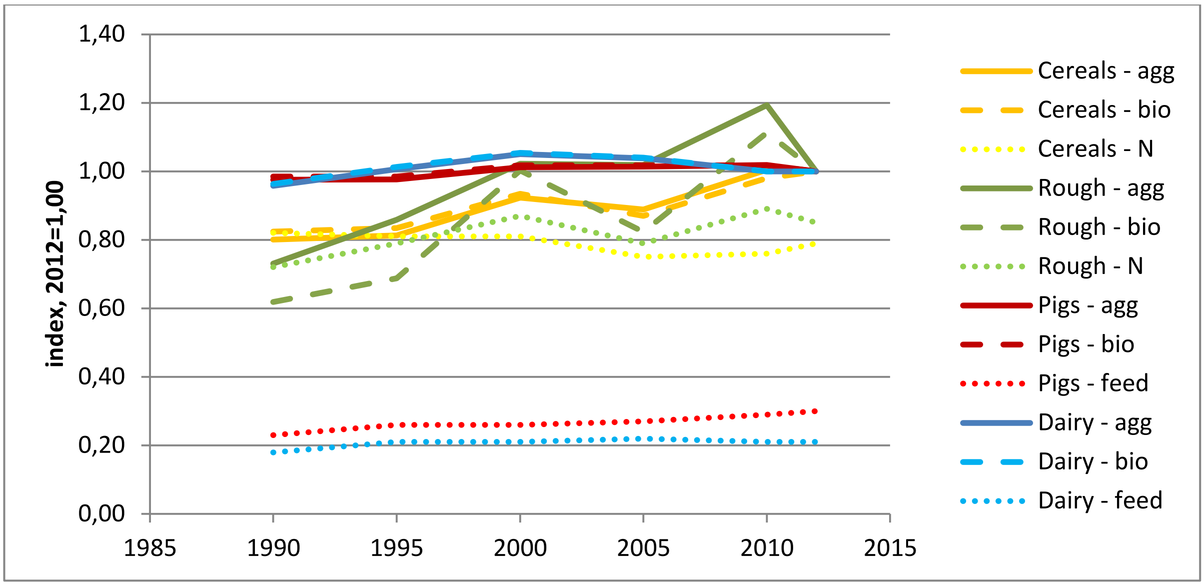

Figure 6. Partial rate of bio-resource productivity and total factor productivity development in cereals, roughage, pigs and dairy cattle, 1990-2012.

The curves show relatively stable rates of productivity in pig and dairy production (both bio-resource and total factor productivity), but significant productivity growth within cereals and roughage production, and for roughage production with quite different patterns for partial bio-resource productivity and total factor productivity, respectively. In addition to the productivity measures established above, we have also included partial technical input conversion rates (input-output ratios for nitrogen in crop production and feed conversion rates in livestock production). It should be noted that whereas the productivity measures are defined with 1.00 as reference value, this is not the case for these technical conversion rates, and hence productivity measures and conversion rates are not comparable in an absolute sense. Nevertheless, comparing their development over time may be meaningful. And in fact, there is a more or less parallel movement in these indicators over time for all four agricultural sectors.

Summing up on figures 5 and 6, the analysis indicates a positive efficiency development in crop production since the early 1990's, particularly in terms of technical efficiency with regard to bio-resources (nitrogen in the case of crop sectors and feed input in the case of livestock sectors), but also in terms of economic efficiency – leading to reduced waste of bio-resources (nitrogen and feed, respectively) during this period. On the other hand, the level of efficiency in livestock production appears to have been quite stable during this period, although some improvement in feed efficiency has occurred.

Using the above developments in resource efficiency, it is possible to calculate counterfactual estimates of absolute *"hidden" food loss*, (i.e. the difference between the actual food production and the amount of food that could have been produced with the applied amount of nitrogen input in case of maximum production efficiency – assuming an N-efficiency in feed production based on mineral fertilizer), using the assumed and calibrated production functions (Box 1 and Table 3). In figure 7, such estimates have been made for cereals and roughage production, using two alternative specifications, referring to the rates of technical and economic food loss, respectively. Hence, "Cereals – econ" refers to the potential output difference between (B_0, C_0) and (B_2, C_2) if maximum efficiency were assumed, and "Cereals – techn" refers to the corresponding potential difference between (B_0, C_0) and (B_1, C_0).

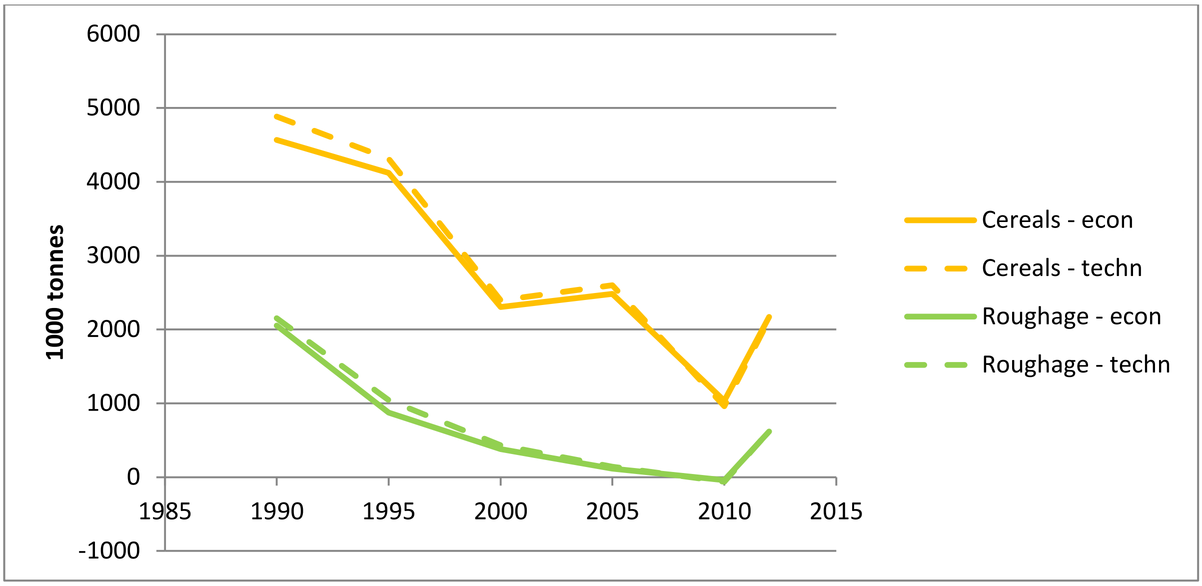

Figure 7. "Hidden" food waste in primary cereals and roughage production

The figure shows a considerable decrease in hidden food loss in the two crop sectors over time – from a total of about 5-6 million tonnes in the two sectors in the early 1990's to about 1.5 million tonnes in recent years. Whether we calculate the hidden food loss on the basis of partial technical N-efficiency or general economic efficiency does not affect the results much.

A corresponding calculation for pig meat and milk is presented in Figure 8. Also for these two sectors, we see a significant decrease over time – and a relatively low sensitivity as to whether we measure the development in food loss according to technical or economic efficiency. Hidden loss of pig meat was about 5-10,000 tonnes per year in the early 1990's, but has decreased to close to zero in recent years. In the same time span, hidden food loss for milk has decreased from 25-35,000 tonnes in the 1990's to 0-2,000 tonnes per year in the most recent years.

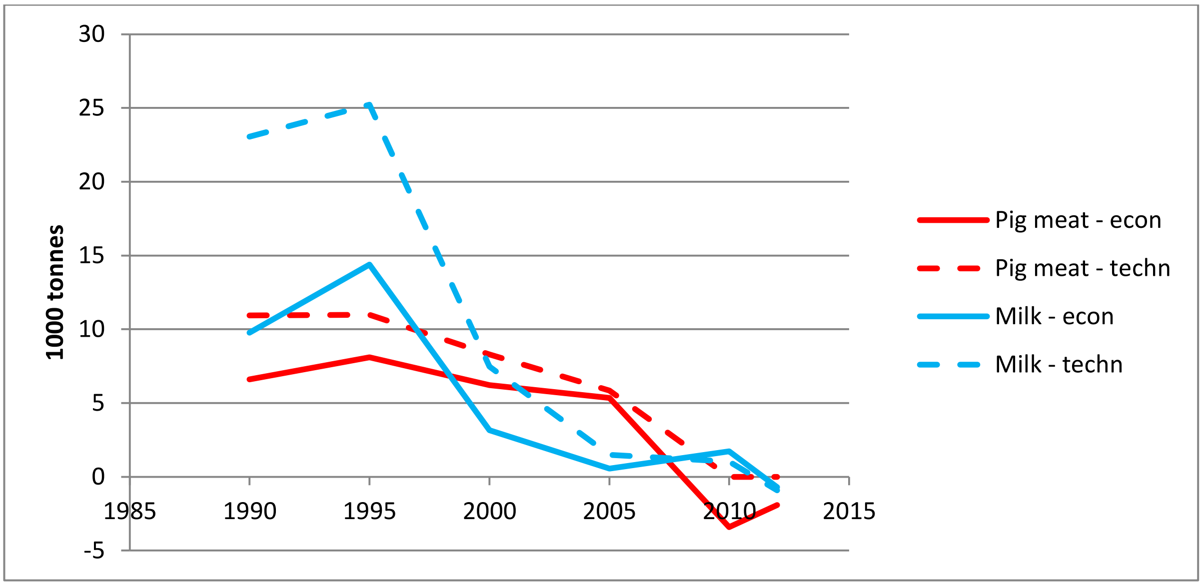

Figure 8. "Hidden" food waste in pig meat and milk production

Summing up on figures 7 and 8, we find that due to increases in production efficiency over time, the "hidden" food loss has decreased substantially since the early 1990's, Again, the uncertainty in the calculations using the relatively simplified model in Box 1 should be underlined – especially in milk production during the most recent years. And for the same reasons as in Figure 5, negative estimated hidden food loss should be interpreted as zero food loss.

Resource efficiency in food processing and distribution

Data on the use of products from agriculture and fisheries have also been collected. Data on the use of fisheries products were collected by the National Food Institute at DTU, and data on the use of agricultural products (cereals and milk) were obtained from Statistikbanken (www.statistikbanken.dk). Figure 9 shows the development in the supply balance for cereals.

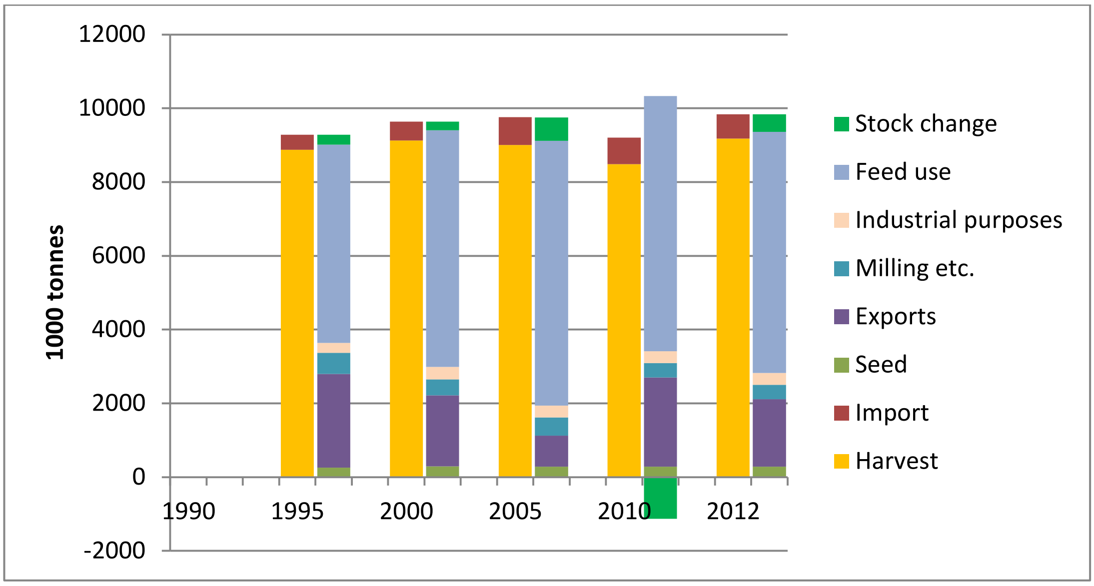

Figure 9. Development of supply balance for cereals, 1990-2012

As the entire supply (except a roughly estimated 2,5% loss in the fields) is used, the data do not show any food loss *per se*. But if some of the uses of cereals could be considered less optimal than others, this could be interpreted as inefficiency in the use of cereals - for example, cereals may have a higher value per kg in milling for human consumption or for brewing than for feed use. In such considerations, quality differences (which may be related to soil type, geography etc.) and demand limitations should be taken into account. The data supply balance data do not provide information about these aspects, so it is not possible to judge the extent of inefficiency in this respect from the data. Nevertheless, figure 8 indicates a decreasing trend in the share of cereal production allocated to milling and an increasing share allocated to feed use, which might suggest an efficiency decrease in the utilization of produced cereals, but might also suggest an increase in efficiency of livestock production – and hence an increasing payoff to the use of cereals for feeding.

A somewhat corresponding supply balance is shown for milk in figure 10 – however dealing only with domestic supply and use. As with cereals, the entire registered production is utilized, and hence there is no milk waste *per se*. Furthermore, the allocation of milk for different end-products also seems to be fairly stable over time – which is naturally related to the utilization of different components (fats and proteins) for different dairy products – and hence the figure does not suggest any trends in the efficiency of utilizing milk in the dairy sector.

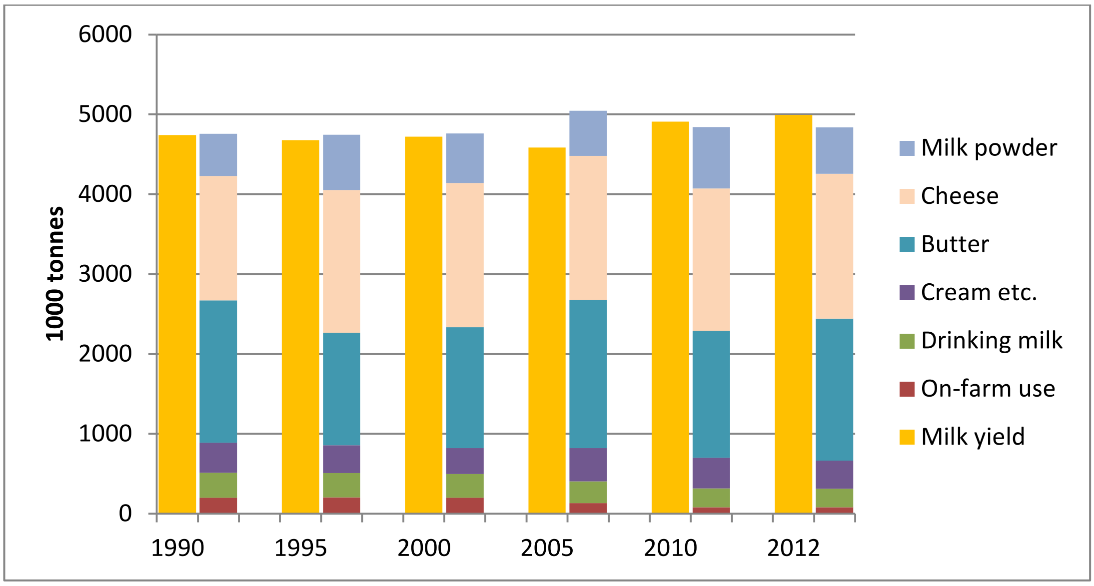

Figure 10. Development of domestic supply balance sheet for milk, 1990-2012

For seafood, supply balance data are only available for 2012, but the date distinguishes four different seafood commodities: fish for consumption, fish for industrial use, shrimps and mussels (figure 11).

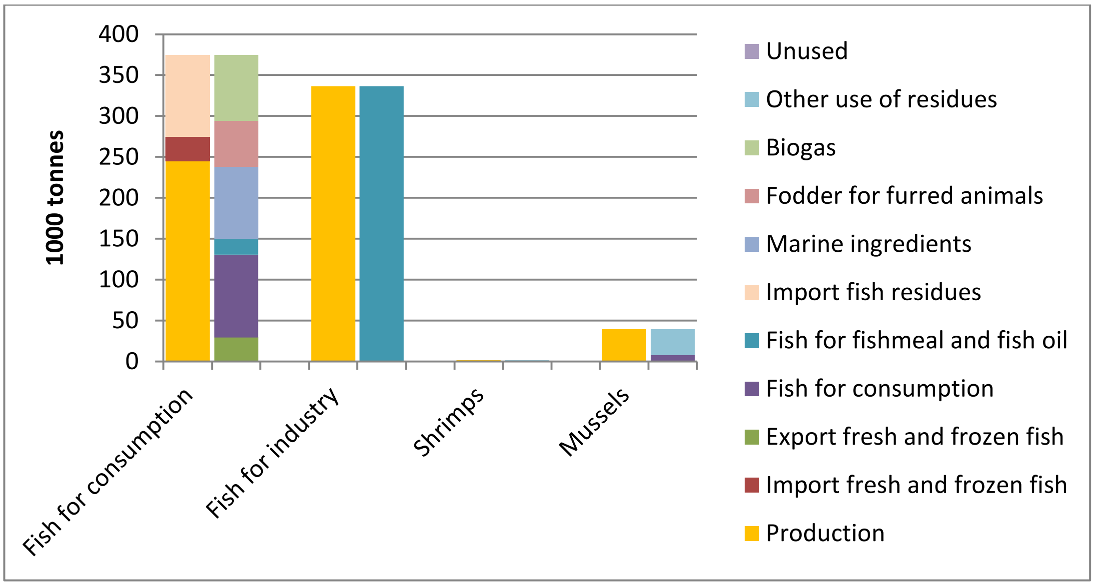

Figure 11. Supply balance for fish, shrimps and mussels, 2012.

Within fish for consumption (from landings and aquaculture), a total supply of about 270,000 tonnes is allocated for exports, human consumption, processing into fishmeal and fish oil (because the landing of about 20,000 tonnes herring are registered as fish for consumption but are actually used for processing), or ends up as residues (heads, bones, skin, intestines, tales etc.). Fish residues from domestic production, together with additional imported fish residues, are processed into fishmeal and fish oil or fodder for furred animals, or are processed in biogas plants, where fish residues enhance gas production. Although the entire fish production hence seems to be utilized, it might be worth considering, if especially the use of fish residues in biogas production could be replaced by more efficient use in the longer run – perhaps after appropriate technological development to extract high-value components of these residues. On the other hand, as fish residues are imported from other countries, utilization of such residues in biogas production in Denmark could be considered to be competitive with other uses – and hence be considered as efficient – at least in the current setting. Currently, 80,000 tonnes of fish residues are used for biogas production, and about 140,000 tonnes are used for mink fodder and fishmeal and fish oil.

For mussels, a relatively large share of the harvest (the shells) is not suitable for consumption. These shells are used e.g. as filling material in road construction. As with the biogas use of fish residues, the development of new technologies might enable more efficient use of these shells in the longer run. If this is the case, this resource constitutes 32,000 tonnes per year.

5. Discussion and conclusions

The present paper establishes an analytical framework for analysing food loss, food waste and resource efficiency in food production. The paper develops a range of indicators for these aspects, and some of these indicators are demonstrated, using Danish production of cereals, roughage, pig meat, milk and seafood as cases, and with a particular focus on the extent of "hidden" food loss in primary agricultural production, and whether there are signs of inefficient use of agricultural and fisheries products in the food processing sectors.

Analyses of hidden food loss in primary agricultural production indicate some degree of resource inefficiency, and that this inefficiency leads to "hidden" food loss, i.e. food production could have been higher, if the applied amounts of inputs had been used more efficiently. The analyses also show that this inefficiency has decreased considerably since the early 1990's – and so has the calculated hidden food loss. It is estimated that the current hidden food loss due to inefficiency in agricultural production amounts to about 1,5 million tonnes from cereals and roughage production, about 1 million tonnes milk and very little pig meat.

From the inspection of supply balance sheets for cereals, milk and seafood products, the extent of resource inefficiency seems to be relatively limited, although development of new processing technologies may open up some opportunities for increased efficiency in the use of residues and by-products from fish and mussel production.

As discussed in the methodology section above, the calculation of hidden food waste in primary production builds on a number of technical assumptions - regarding functional form of the production technology, as well as key parameters such as elasticity of substitution between bio-resource inputs and other inputs. Sensitivity analyses with respect to the elasticity of substitution show that larger elasticity of substitution implies a larger estimate of hidden food loss for cereals, pig meat and milk, whereas the food loss estimate for roughage is fairly robust to the elasticity assumption. The results are also fairly sensitive to the assumed TFP efficiency rates, cf. Table 3, in that lower efficiency rates would imply larger unused potentials for improvement and hence larger hidden food waste. As the study of Rasmussen (2010) builds on full-time farms, this is likely to be the case.

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