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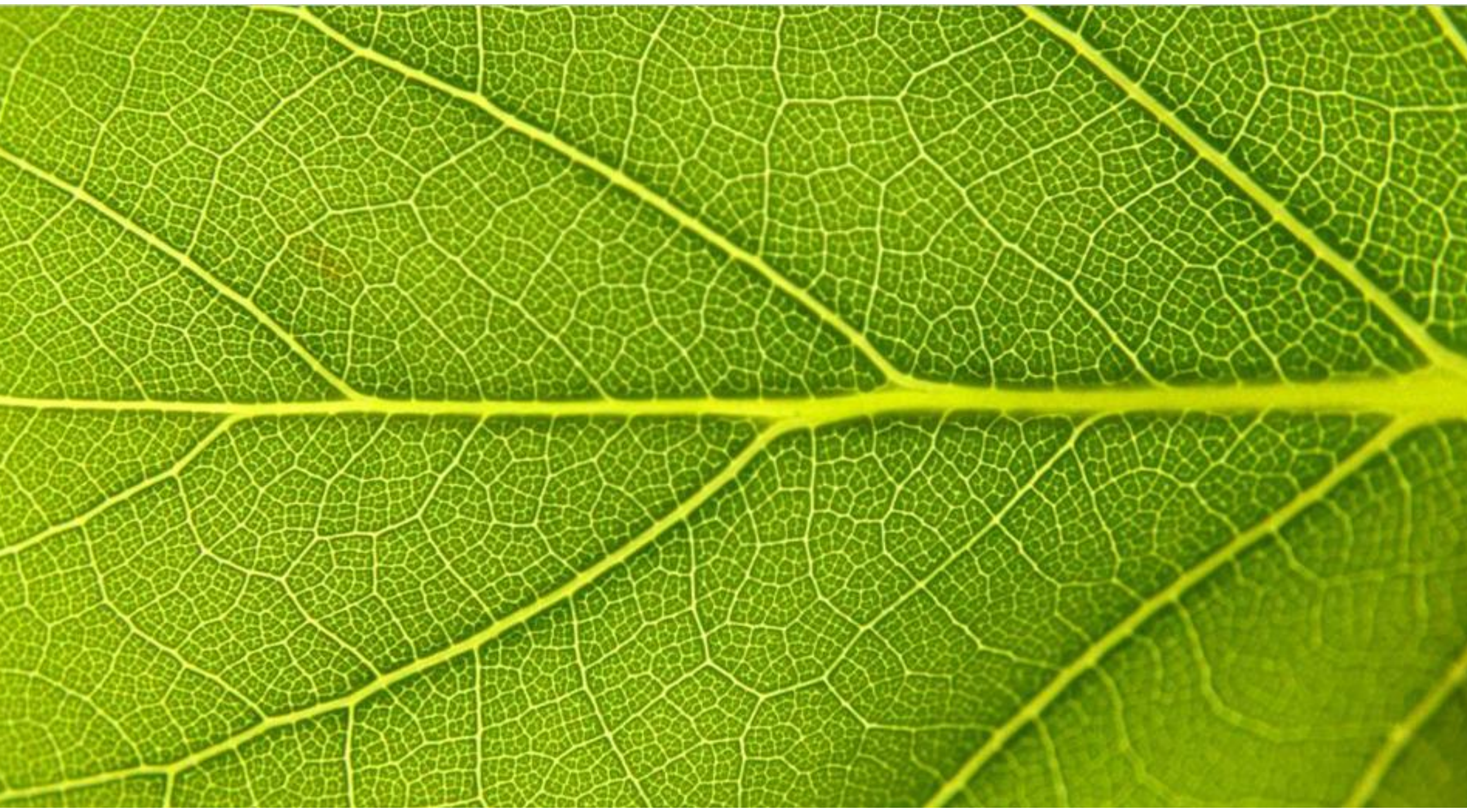

Beef and milk: Emission intensities of intensive and extensive production system on regional and global level in 2010

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1. EXECUTIVE SUMMARY

In December 2015 at the 21st COP 195 countries agreed to maintain this 2°C limit and drive efforts to limit the temperature increase even further to 1.5°C (UNFCCC, 2015). This agreement represents a key step forward in developing strategies to reduce the emission of greenhouse gases (GHGs) and building a sustainable future. However, there is "lack of consistent methods for companies to align their emission targets with global climate scenarios" (Science Based Targets, 2015). The Sectoral Decarbonization Approach (SDA) is a methodology that helps companies set sector specific emission reduction targets in line with the 2°C scenario. To date, the Agriculture, Forestry and Other Land Use (AFOLU) sectors *lack an equivalent science based methodology*. This research contributes expansion of Science Based Targets to the AFOLU sector. The commodities analysed in this research are be beef and cow milk as their emissions constitute a large part of the AFOLU GHG emissions – 22.6% (CEA, 2014) (Cubasch, 2014a). Emissions taken into account are all non-CO_2 on-farm emissions: CH_4 emissions originating from enteric fermentation and manure, direct N_2O emissions from manure both deposited while grazing and managed in stables and indirect N_2O emissions from soil leaching and runoff and volatilization. The main research question is: What are the emission intensities of beef and milk for intensive and extensive production systems on regional and global level in 2010?

The methodology follows the procedure: emission calculation, emission allocation and emission intensity calculation. The emissions are calculated for both dairy and non-dairy cattle per production system on a global and regional level (25 regions are included). The methodology mainly follows the tier 1 methodology from the IPCC Guidelines (IPCC, 2006). Emissions from dairy cattle are then allocated partially to beef and partially to milk. All emissions from non-dairy cattle are allocated to beef. Two allocation techniques are used: physical (adopted by the International Dairy Federation (International Dairy Federation, 2015) and economic (based on market prices of the commodities). The emission intensities are then calculated by dividing the emissions for beef and milk by the production volumes of the respective product.

In general, more emissions are allocated to beef and less to milk when using economic allocation. For beef, the extensive method is generally more emission intense with certain cases of exception, while for milk results vary. With physical allocation for beef the worst performing region is India+ (75.6 & 82.6 kg CO_2e/kg CW beef). The region Asia-Stan performs best for intensive (4.8 kg CO_2e/kg CW beef) and Canada for extensive (26.2 kg CO_2e/kg CW beef). With physical allocation for milk the worst performing regions are Western Africa for intensive (3.6 kgCO_2e/kg milk) and China+ for extensive (17.1 kgCO_2e/kg milk). The best performing ones are Oceania (0.2 kgCO_2e/kg milk) for intensive and Turkey (0.1 kgCO_2e/kg milk) for extensive. With economic allocation for beef the worst performing regions are Turkey for intensive (104.3 kgCO_2e/kg CW beef) and Northern Africa for extensive (166.1 kgCO_2e/kg CW beef). The region Asia-Stan performs best for intensive (8.6 kgCO_2e/kg CW beef) and Canada for extensive (27.8 kgCO_2e/kg CW beef) (same as the results from physical allocation). With economic allocation for milk the worst performing regions are Eastern Africa for intensive (2.6 kgCO_2e/kg milk) and China+ for extensive (6.8 kgCO_2e/kg milk). The best performing ones are Korea for intensive (0.1 kgCO_2e/kg milk) and Turkey for extensive (0.1 kgCO_2e/kg milk).

This study recommends using physical allocation when analysing beef and milk or edible animal co-products. This is mainly because economic allocation while being simple is too market based. Physical allocation is more data intensive, however reflects the underlying use of feed energy to produce the edible products.

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3. LIST OF ABBREVIATIONS

2DS- 2 degree scenarios

AF – Allocation factor

AFOLU - Agriculture, Forestry and Other Land Use

CDP - the Carbon Disclosure Project

CMWG – Cattle Model Working Group

COP - Conference of the Parties

CW – Carcass weight

ETP - Energy Technology Perspectives

FPCM – Fat and protein corrected milk

GHG - greenhouse gas

GLEAM - Global Environmental Assessment Model

GWP – Global warming potential

IDF – International Dairy Federation

IEA - International Energy Agency

ILUC - Indirect land use change

IMAGE- Integrated Model to Assess the Global Environment

IPCC – Intergovernmental Panel on Climate Change

ISO – International Standardization Organization

LCA – Life Cycle Assessment

LUC - Land use change

LW – Live weight

RCP - Representative Concentration Pathway

SBT - Science Based Targets

SDA - Sectoral Decarbonization Approach

SSP - Shared Socioeconomic Pathway

UNFCCC - United Nations Framework Convention on Climate Change

UNGP - UN Global Compact

WRI - World Resource Institute

WWF - World Wide Fund for Nature

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5. INTRODUCTION

5.1 PROBLEM DEFINITION AND SOCIAL AND SCIENTIFIC RELEVANCE

At the 16th Conference of the Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCCC) in 2010, for the first time in history, parties agreed to maintain the mean surface temperature (MST) increase below 2°C relative to pre-industrial levels (UNFCCC, 2010). In December 2015 at the 21st COP 195 countries agreed to maintain this 2°C limit and drive efforts to limit the temperature increase even further to 1.5°C (UNFCCC, 2015). This agreement represents a key step forward in developing strategies to reduce the emission of greenhouse gases (GHGs) and building a sustainable future. The 2°C limit has been accepted by the majority of the scientific community as an "upper limit beyond which climate change becomes catastrophic and irreversible" (Science Based Targets, 2014). According to Cubasch et al. (2014a) the emission scenarios that would likely maintain this limit are the ones leading to a CO_2e concentration of 450 ppm or lower, i.e. the scenario RCP 2.6[1]. However, the current trends are pointing towards a different trajectory, with rates of emissions increasing and indicating that the 450 ppm threshold will be exceeded by 2030 (Science Based Targets, 2014). This business as usual scenario would lead to an increase of the MST of 3.7°C -4.8°C in 2100 (Cubasch, 2014a), levels of increase which are far beyond the ones that the scientific and international community have identified as safe (Science Based Targets, 2014).

Keeping the temperature increase below the 2°C limit requires a total reduction of CO_2e emissions compared to 2010 of 41%-72% until 2050 and of 78%-118% until 2100 (Cubasch, 2014a). Taking 2010 as a base year and assuming a linear trajectory, staying within the limit would require a decadal reduction of 10%-18% CO_2e emissions (Science Based Targets, 2014). These numbers point to the urgent need of fast decarbonisation of the current economy. Many businesses are already taking actions for reducing their carbon footprint. As reported by the Carbon Disclosure Project (CDP) in 2013, approximately 81% of the Global 500 companies have implemented targets for emission reductions (CDP, 2013). However, a big share of these targets is usually conservative and only responsive to existing regulations or projects in the short-term. In addition, the emissions from leading emitters from each economic sector have increased over the past 5 years (CDP, 2013). The alarming scientific projections, the continuous increase of GHG emissions, and the valuable but not yet significant action of businesses call for more drastic emission reduction measures.

This current situation has lead CDP, World Resource Institute (WRI), World Wide Fund for Nature (WWF), and UN Global Compact (UNGP) to thinking that one of the reasons for inaction or insufficient action from businesses is the "lack of consistent methods for companies to align their emission targets with global climate scenarios" (Science Based Targets, 2015) and the inability to translate climate scenarios to their specific activities. Thus, in a joint effort, these organizations have initiated the Science Based Targets (SBT) program, which is intended to "increase corporate ambition on climate change". The latest SBT methodology for setting emission reduction targets is the Sectoral Decarbonization Approach (SDA) which was developed by the CDP, WRI and WWF with the technical support of Ecofys, the consultancy partner. The SDA is a methodology that helps companies set sector specific emission reduction targets in line with the 2°C scenario developed by the International Energy Agency (IEA) (Science Based Targets, 2015) and builds on a concept of carbon budget, introduced by the IPCC. According to Cubasch et al. (2014a) in order to stay below the limit of 2°C warming until 2100, we need to limit the total anthropogenic carbon emissions (the leftover carbon budget) that can be emitted as of 2011 to 1,010 $GtCO_2$e. The companies get a carbon budget allocated according to their "contribution to the economy and value-added" (Science Based

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[1] RCP: Representative Concentration Pathways

Targets, 2015) and can look at their commodity specific emission reduction targets. Currently, the SDA covers sectors that are responsible for almost 60% of the global GHG emission budget including the sectors: industry, transport, electricity and heat and buildings (Science Based Targets, 2015).

To date, the Agriculture, Forestry and Other Land Use (AFOLU) sectors *lack an equivalent science based methodology*. AFOLU commodities ranging from rice and maize to beef and round wood, have a large impact on the environment and emit a great amount of GHG, both during their land preparation (e.g. deforestation), production and post-production (e.g. residue burning) stages. The emissions from AFOLU constituted 24% of the total global GHG emissions in 2010 (Cubasch, 2014a). These emissions are expected to continue to rise with the projected increase in both global population and demand for AFOLU commodities. It is clear that the AFOLU sectors are and will continue to be significant contributors to GHG emissions which *urges towards a development of a science based target setting methodology for the AFOLU commodities.*

Funded by KR Foundation, Ecofys, together with PBL Netherlands Environmental Assessment Agency and the University of Aberdeen, are developing a methodology that enables companies who produce and/or use AFOLU commodities (ranging from farmers to retailers) to align their activities with what is required to limit the temperature increase to 2°C relative to pre-industrial levels. The amount of decarbonisation required of the commodities will be estimated per commodity with help of emission intensity reduction pathways towards 2050 for 10 key commodities. The 10 key commodities are the following: beef, dairy, pigs, poultry/chicken, rice, maize, wheat, soy, palm oil and round wood. These commodities have been selected as a starting point according to the following criteria: GHG impact, market shares, change potential, and strategic relevance. From figure 1 we can see that in 2010 9 of these 10 commodities contributed to a total of 42.2% of the GHG emissions from the whole AFOLU sector.

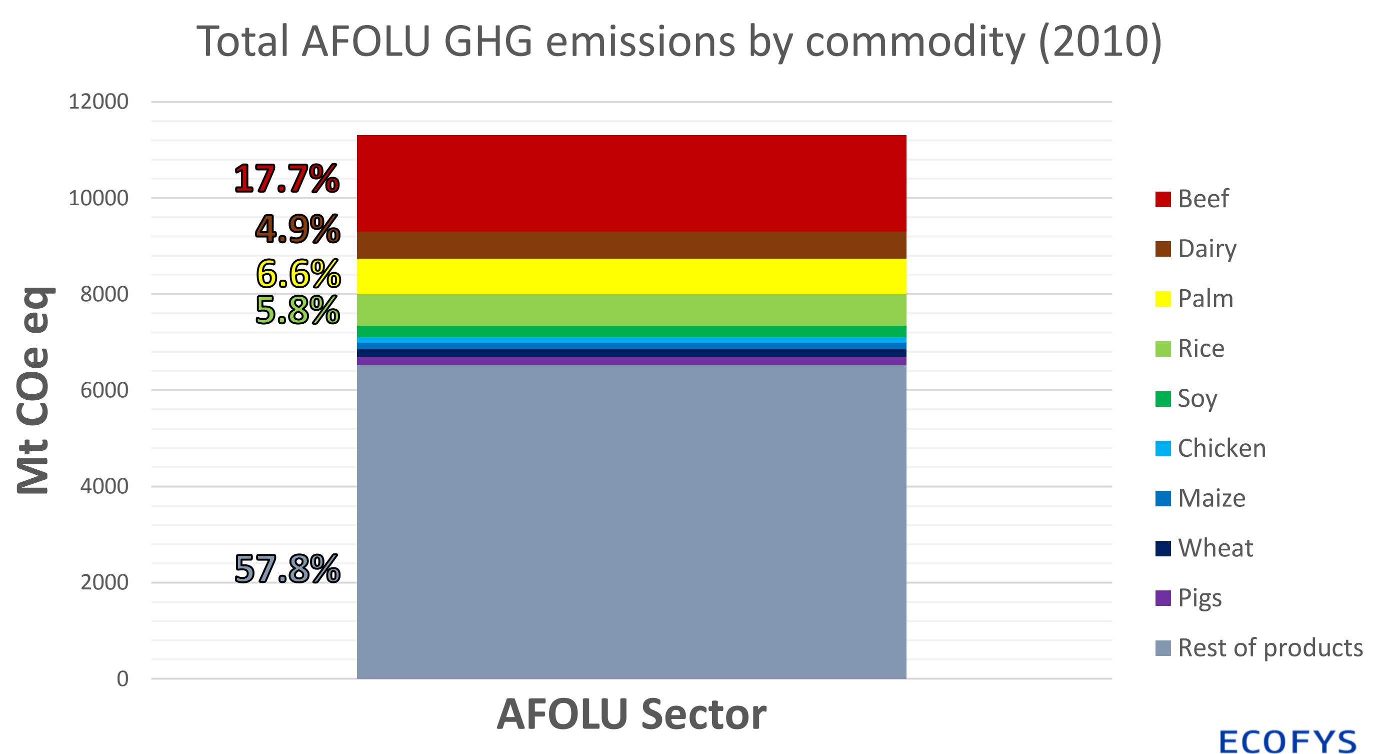

Figure 1. Total AFOLU GHG emissions per commodity for 2010 (Cubasch, 2014a); (CEA, 2014).

5.2 AIM AND RESEARCH QUESTION

The commodities analysed in this research are beef and cow milk (from now on referred to as 'milk') as their emissions constitute a large part of the AFOLU GHG emissions – 22.6% (Figure 1). The overall aim of this internship is to make a contribution to the expansion of Science Based Targets to the AFOLU sector by calculating the emission intensities of beef and milk for the base year 2010 for two production systems, intensive and extensive, on a regional (25 world regions) and global level. This was be done firstly calculating the on-farm non-CO_2 emissions for dairy producing and meat producing cattle (from now on referred to as 'dairy and non-dairy cattle'), and then dividing these emissions by the production volumes of beef and milk respectively. The research puts an emphasis on allocation of emissions to milk and beef as co-products from dairy cattle; while all emissions from the non-dairy cattle are assigned to beef. Data used is from the Integrated Model to Assess the Global Environment – IMAGE, developed by PBL Netherlands Environmental Assessment Agency. The main research question is as follows:

What are the emission intensities of beef and milk for intensive and extensive production systems on regional and global level in 2010?

A number of sub-questions are answered to support the main research question, namely:

- What on-farm agricultural processes are involved in the production of beef and milk?
- What are the emissions of the relevant agricultural processes?
- What methods of emission allocation to beef and dairy are used by the LCA community?
- What are the differences in the outcomes from the different allocation methodologies?
- Are (parts of) the current allocation methodologies applicable for this project?

5.3 SETTING BOUNDARIES

This research mostly follows the scope and boundaries of the SDA. The *aggregation* of the emission intensities are on commodity level. The *time scope* for the emission intensities is 2010, as the SDA takes 2010 as the base year due to the use of a 5 year time unit (similar to the IEA), the fact that data for 2015 is not yet available. The *time scope* for the MST increase target temperature is year 2100. The functional unit is kg CO_2e/kg CW beef (carcass weight) for beef and kg CO_2e/kg milk for milk.

The system boundary is farm-gate to farm-gate, meaning all on-farm CH_4 and N_2O (direct and indirect) emissions from livestock are taken into account. CH_4 emissions originating from enteric fermentation and manure are included. Direct N_2O emissions from manure both deposited while grazing and managed in stables and indirect N_2O emissions from soil leaching and runoff and volatilization are also included (Figure 2). CO_2 on-farm energy use emissions (for milking, ventilation, lighting etc.) are excluded from the analysis due to lack of appropriate data. When looking at global average figures, this exclusion does not have a great effect on the results, as on-farm energy use emissions comprise only approximately 1.8% for beef and 3.7% from milk of all on-farm emissions (section 10, Figure 12) (Gerber, 2013). However, emissions from on-farm energy use can have greater effects when considering certain regions and production systems (for more details see section 10, figures 13 & 14). Furthermore, all emissions originating from feed production such as fertilizer production and use both organic and synthetic (CO_2 and N_2O), crop residues (N_2O), machinery use (CO_2) are excluded. The reason behind this exclusion is that these emissions are a part of other sectors in the SDA and if included in this analysis they will be a subject to double counting. However, as these constitute a big part in the total emissions of livestock products their implications on the results is elaborated on in the discussion chapter. All land use change (LUC) emissions such as any type of conversion of land, grassland and savannah burning, deforestation, peat degradation and all indirect land use change (ILUC) emissions are excluded. PBL Netherlands Environmental Assessment Agency has taken the lead on allocation of (I)LUC emissions. The *geographical scope* of the research is global but with a distinction between 25 regions (modelled in IMAGE) in order to take into account regional differences in demand, yield, efficiency, soil type etc.

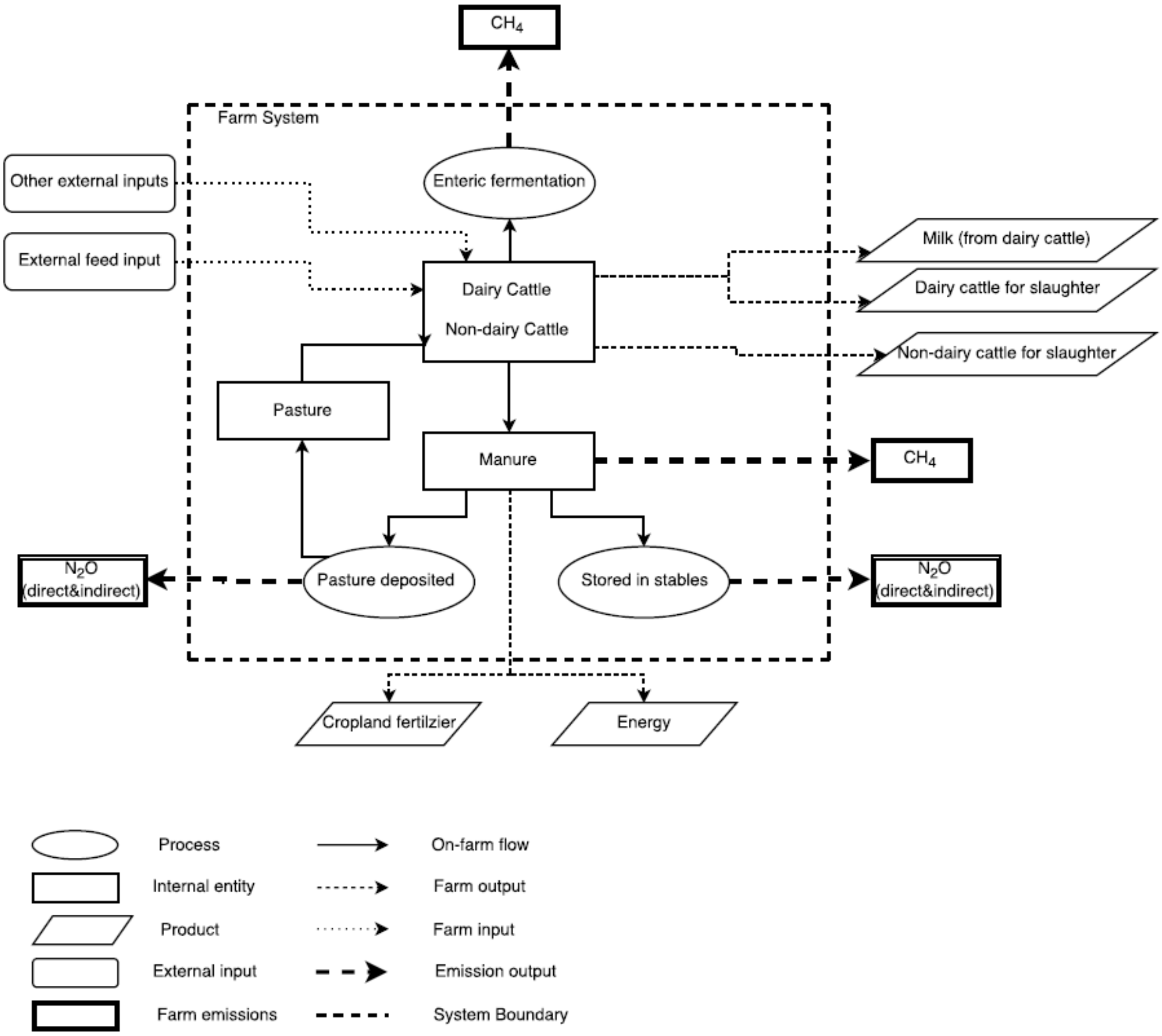

Figure 2. System boundaries

5.4 OUTLINE OF REPORT

The next section presents the theoretical background of this analysis. Section 7 describes the methodology used for emission calculation, allocation and calculation of the emission intensities. In section 8 the needed input data is presented. The results are shown and elaborated in section 9. Section 10 gives a thorough discussion on the results, emission scope, other methodological choices, recommendations and presents that data available/missing in order to construct the emission intensity pathways to 2050. The conclusions of this analysis are presented in section 11.

6. THEORETICAL BACKGROUND

6.1 THE SECTORAL DECARBONIZATION APPROACH (SDA)

The SDA is a methodology developed to help companies commit to a long-term vision towards a low-carbon economy and adopt actions that are in line with the existing scientific literature and approaches. The main target of the SDA is aligning corporate emissions with the 2°C increase in MST limit. This method allocates allowances of GHG emissions (a.k.a. carbon budget) to sectors by taking inherent sectorial differences into account and thus setting a fair share contribution to the 2°C goal. The differences between sectors that the SDA takes into account include mitigation potentials and activity growth which is relative to population and economic growth (Science Based Targets, 2015).

The backbone of the SDA consists of two reports: the fifth Assessment report of the IPCC (2014) and Energy Technology Perspectives of the International Energy Agency (2014). The 5th Assessment report presents the concept of the global carbon budget. The carbon budget requires the total anthropogenic GHG emissions to stay below 3670 $GtCO_2$ since the period 1861-1880 in order to limit the warming caused by anthropogenic CO_2 emissions to less than 2°C (Cubasch, 2014a). When non-CO_2 gasses are accounted for, on the basis of their radiative forcing, they indirectly lower the carbon budget to 2900 $GtCO_2$ (Cubasch, 2014a). As the total anthropogenic emissions up until 2011 are 1890 $GtCO_2e$, the remaining carbon budget from 2011 onward is 1010 $GtCO_2$ (Science Based Targets, 2015). As mentioned before the IPCC scenario that gives the best chance (66%-100%) of staying in line with the 2°C limit is the RCP 2.6. This scenario corresponds to a concentration of 450 ppm CO_2e in 2100 and estimates global anthropogenic emissions of 990 $GtCO_2$ up to 2050 (Science Based Targets, 2015). As these emissions are compatible with the global carbon budget, the RCP2.6 scenario is the basis of the SDA.

The Energy Technology Perspectives (ETP) of the IEA presents a detailed 2°C CO_2 scenario that has a breakdown for all the sectors currently included in the SDA. The 2°C scenario (2DS) from the IEA is in line with the RCP2.6, which makes it compatible for the SDA**.** The SDA uses the detailed 2°C sector-scenarios from the International Energy Agency (IEA 2DS) model to derive a sector specific carbon intensity pathway compatible to the 2°C target (Science Based Targets, 2015). This is done by dividing the total direct emissions of the sector with the total activity of that specific sector in a given year. Using the sector specific carbon intensity, companies, within that sector, can then derive their science based emission reduction targets based on their relative contribution to the total activity of the sector and their carbon intensity relative to the intensity of the sector in the base year (Science Based Targets, 2015). The total carbon budget of the company from the base year to the target year can then be calculated by multiplication of the projected activity yield and the company's intensity pathway.

6.2 ALLOCATION METHODS IN LCA LITERATURE

6.2.1 STANDARDS AND GUIDELINES

The emission allocation procedures to beef and milk as co-products are heavily discussed in the literature. There are multiple standards and guidelines of the allocation hierarchy that LCA practitioners are advised to follow. Table 1 presents these reports and their allocation guides.

Name	Type	Year	Allocation methods
ISO 14044:2006 (ISO 14044, 2006)	Standard	2006	ISO allocation procedure
ILCD Handbook (European Commission- Joint Research Cenre - Institute for Environment and Sustainability, 2010)	General Guide	2010	ISO standards apply
PAS2050 (PAS 2050:2011, 2011)	Specification	2011	ISO standards apply
GHG Protocol: Product Life Cycle Accounting and Reporting Standard (Greenhouse Gas Protocol, 2011)	Standard	2011	ISO standards apply
Harmonizing footprint PEFs (European Comission, 2013)	Standard	2013	ISO standards apply
Cattle model working group (CMWG) (European Comission JRC - Cattle Model Working Group, 2013)	Baseline approaches	2013	ISO and PEF standards apply; A recommendation to use the IDF biophysical allocation method for meat and milk as co-products
A common carbon footprint approach for dairy: The IDF guide to standard LCA methodology for the dairy sector (International Dairy Federation, 2015)	Guide	2015	ISO standards apply: For the production of meat and milk as co-products most appropriate approach is the physical allocation method.

Table 1. Overview of reports and their allocation guides

All the reports take the ISO 14044:2006 standards as a basis for allocation procedures. The choice of allocation methods given by ISO 14044 follows the stepwise procedure hierarchy:

Step 1: Whenever possible the allocation should be avoided by:

a) Unit process division into more sub-processes and obtaining input/output data for these sub-processes;
b) Product system expansion by including additional functions related to the co-products

Step 2: If allocation cannot be avoided by following step 1 procedures, “the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects relevant underlying physical relationships between them” (ISO 14044, 2006) such as mass, energy etc.

Step 3: When physical allocation cannot be used the inputs/outputs “should be allocated between the products and functions in a way that reflects other relationships between them” (ISO 14044, 2006), e.g. in proportion to the economic value of the co-products.

The standard also addresses outputs that are partially co-products partially waste, in which case the ration between the co-products and waste should be identified so the inputs/outputs can be allocated to the co-products only (ISO 14044, 2006).

Three reports have addressed preferences in the allocation procedures. The GHG Protocol lists a couple of situations for distinguishing preference between physical and economic allocation. Namely physical allocation should be preferred when: The physical relationship that is established reflects the co-products' relative emission contributions; and changes in the process emissions result in a change in the physical output and the co-products' market values do not reflect their relative emission contributions (Greenhouse Gas Protocol, 2011). On the other hand, according to the GHG protocol (2011) economic allocation should be preferred when: any type of physical relationship cannot be established or it does not properly reflect the co-products' relative emission contributions; the co-products would not be produced as a separate product without the market demand for the main product; the co-product is a waste output which then has acquired a market value by replacing another material input (Greenhouse Gas Protocol, 2011).

The IDF guide (International Dairy Federation, 2015) and CMWG (European Comission JRC - Cattle Model Working Group, 2013) have directly addressed the co-production of milk and meat. The International Dairy Federation (2015) conveys a strong stand for using the physical allocation method for co-product allocation between milk and meat and presents a detailed procedure on how this should be done. The reasoning behind supporting the physical allocation method is that it aligns with the ISO 14044 standards and "reflects the underlying use of feed energy by the dairy animals and the physiological feed requirements of the animal to produce meat and milk" (International Dairy Federation, 2015). Further, the main factor in determining the amount of CH_4 emissions from enteric and the CH_4 and N_2O emissions from animal manure is the feed consumption by animals (International Dairy Federation, 2015). The IDF uses the following equation to calculate the allocation factor (AF) for milk:

$$AF_{milk} = 1 - 6.04 * BMR \tag{1}$$

$$AF_{meat} = 1 - \ AF_{milk} \tag{2}$$

In eq.1 BMR[2]=M_{meat}/M_{milk}, M_{meat}[3]= sum of live weight of all animals sold and M_{milk}= sum fat and protein corrected milk (FPCM) milk sold. FPCM is the functional unit that IDF uses and it is used in order to assure fair comparisons among farms with different feeding or breeding regimes that can result in milk with different fat and protein contents. FPCM is calculated using the following equation:

$$FPCM\ \left[\frac{kg}{yr}\right] = Production\ \left[\frac{kg}{yr}\right] * (0.1226 * Fat[\%] + 0.0776 * TrueProtein[\%] + 0.2534) \tag{3}$$

In eq.3 Fat% is the percentage of fat in the specific farm product and TrueProtein% is the percentage of true protein in the specific farm product. The standard fat and protein corrected milk has 4% fat and 3.3% true protein.

The empirical relationship (eq.1) for the allocation factor of milk is derived from a large study performed by Thoma et al. (2013). The study uses detailed data on a farm-level from 536 US farms to develop a causal relationship between the energy content in the animal feed ration and milk and beef production (International Dairy Federation, 2015). The study of Thoma et al. (Thoma, 2013) found that feed energy available for milk production, for a given feed, is greater than the feed energy available for growth (i.e. meat production). Meaning, the conversion of feed to milk is a more efficient use of feed (International Dairy Federation, 2015). Using this causal relationship between

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[2] BMR is the beef to milk ratio. A default value of BMR=0.02 kg_{meat}/kg_{milk} is given, which results in a default AF_{milk}=88% and AF_{meat}=12% (IDF, 2015)

[3] This excludes on-farm dead animals

the feed as farm input and the meat and milk as farm outputs an algorithm for estimation of the quantity of feed requirements for producing the observed quantities of milk and meat is created. This algorithm using 160 different rations of feed as farm inputs is then applied in order to calculate the causal allocation factor for each of the 536 farms (International Dairy Federation, 2015). The formula for the allocation factor of milk (eq.1) is then fitted as an empirical relationship to simplify the application of the approach and is regarded to be robust enough to be used on an international level (International Dairy Federation, 2015) (See figure A.1 of appendix A). The CMWG adopts this procedure and presents it as a baseline approach in its allocation methods. It should be noted that this allocation should only be applied to emissions that cannot be attributed to only beef or milk (e.g. enteric fermentation from dairy cattle that also produces beef). Emissions from electricity use for milking, on the other hand, should not be allocated between the co-products, but entirely to milk (International Dairy Federation, 2015).

The ISO 14044:2006 gives economic allocation as a last resort. However, the majority of LCA studies choose to use this allocation method mainly due to data accessibility. The economic allocation method uses the following formulas for determining the allocation factors:

$$AF_{milk} = \frac{M_{milk} * Price_{milk}}{(M_{milk} * Price_{milk} + M_{meat} * Price_{meat})} \tag{4}$$

$$AF_{meat} = 1 - AF_{milk} \tag{5}$$

The value of prices used in this equation should be the average producer prices (prices that farmers get at farm-gate) over the last 5 years (Opio, 2013).

6.2.2 METHODS IN LITERATURE

Methods used in literature vary. The main reasons for variation are data availability, system boundaries, goal of the study, co-products taken into account and preferences. All allocation practices have their advantages and disadvantages which are listed throughout the literature.

a) AVOIDING ALLOCATION

Schenck & Huizenga (Schenck, 2014) state that the option of avoiding allocation via system expansion is feasible for co-products that can be produced by other processes, which is problematic when looking at agricultural products. If we take a case of a dairy herd producing milk, cull cows and calves and try to establish a process that results in a product similar to cull cows (i.e. beef) one can state a suckler cow herd to be an alternative system i.e. producer of beef (Schenck, 2014). According to Schenck & Huizenga (Schenck, 2014) this system expansion is not satisfactory as these two different products have different qualities. Establishing an alternative production of cow milk is even more difficult and using processes for producing goat milk or soy milk are options however these are very different product than cow milk (Schenck, 2014).

A study of Cederberg & Stadig (Cedeberg, 2003) shows that when the system expansion avoiding allocation process is used the milk system is assigned with barely two thirds of the GHG emissions, which leads to an underestimation of the product emission intensity.

b) PHYSICAL ALLOCATION

Physical allocation methods, especially based on protein content, are supported in literature mainly because the method directly reflects the primary function of the products – to provide consumers with edible protein (Opio, 2013). Advantages of using the protein content allocation is that: it is stable through time, direct comparison between products is enabled and can be applied in absent market situations (Opio, 2013). A disadvantage is that all the other nutritional properties are neglected (Opio, 2013).

c) ECONOMIC ALLOCATION

The economic allocation method is the most discussed one in literature as it is also the most often used one despite the fact that the ISO 14044:200 standards propose it as a last option. The greatest advantage of this method is its inferiority to the physical one with respect to data availability (European Commission- Joint Research Cenre - Institute for Environment and Sustainability, 2010). In addition, it is attractive since it represents the value created by the process (Schenck, 2014). The greatest disadvantage of this method is that it depends on time and place as the fractions of allocation vary together with variations in the economics of the industries in relation several aspects such as demand, supply, culture, subsidies, technological development etc. (International Dairy Federation, 2015); (Schenck, 2014). These types of variations affect the allocation factors and the credibility of the analysis (Schenck, 2014).

d) OTHER

A study by Lesschen et al. (J.P. Lesschen, 2011) uses a totally different approach for emission allocation. In this study all emissions coming from mature dairy cows are attributed to milk, while all emissions from calves and heifers are attributed to beef (J.P. Lesschen, 2011). This is an example of approaches that are tailor made according to the specific aim of a study and the data availability while not following the prescribed ISO LCA standards.

6.3 IMAGE

IMAGE is an integrated model to assess the global environment. It is developed by PBL Netherlands Environmental Assessment Agency. The IMAGE 3.0 framework is the latest update of the model. It addresses a set of global sustainability challenges and environmental issues such as water scarcity, land use change, climate change modified nutrient cycles and biodiversity loss (Stehfest, 2014). The objectives of the integrated model are:

- Analysis of the long-term and large-scale interactions between the natural environment and human development; (Stehfest, 2014)
- Identifying response strategies to global environmental change based on assessment of options for adaptation and mitigation (Stehfest, 2014);
- Indicating the key interlinks and the relating level of uncertainty in the process of environmental change (Stehfest, 2014).

The model is usually used to explore two type of issues, namely: (1) how the future unfolds if no change in the prevailing economic, technological or policy systems is made a.k.a. business as usual scenario; (2) how different measures and policies can prevent unwanted impacts on the environment (Stehfest, 2014). In the second case, alternative scenarios are developed which explore possible solutions to an environmental problem.

IMAGE 3.0 has a wide spectrum of outputs with a temporal scope of 1970-2100. The outputs relevant to this research are:

- Agricultural production (in kg CW beef and kg milk)
- Atmospheric emissions of GHGs (kg CH_4 and kg N_2O)

The output of agricultural production is given on a commodity level (beef and milk) and is directly applicable in this research. Milk production, however, encompasses all types of milk, namely milk from cows, buffaloes, sheep and goats. This is corrected for in the methodology by assuming that the percentage share of cow milk out of the total milk production volume in IMAGE is equal to the one from FAOstat's Global Livestock Environmental Assessment Model (GLEAM).

The output of GHG emissions, on the other hand, is given on an agricultural process aggregation level with no distinction by animal type. For instance, the outputs only give total emissions from enteric fermentation from all animals. This makes the outputs not applicable for this research and it is the reason why the emissions in this analysis are calculated using intermediate IMAGE outputs and data following the IPCC guidelines (IPCC, 2006).

IMAGE distinguishes two livestock production systems: extensive (pastoral grazing) and intensive (mixed and industrial) based on FAO[4] (Stehfest, 2014). The intermediate outputs of IMAGE are differentiated in the two production systems (unless otherwise specified).

In order to account for spatial differences, the IMAGE model provides regional output. The regions included in this analysis are: Canada, USA, Mexico, rest of Central America, Brazil, Rest of South America, Northern Africa, Western Africa, Eastern Africa, Southern Africa, OECD Europe, Eastern Europe, Turkey, Ukraine & Belarus, Asia-Stan, Russia+, Middle East, India+, Korea, China +, South East Asia, Indonesia +, Japan, Oceania and Greenland. In addition, this analysis includes results on a global level.

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[4] *Grazing systems*: "Livestock systems in which more than 90% of dry matter fed to animals comes from rangelands, pastures, annual forages and purchased feeds and less than 10% of the total value of production comes from non-livestock farming activities" (Seré C., 1996)
Mixed systems: Livestock systems "in which more than 10% of the dry matter fed to livestock comes from crop by-products and/or stubble or more than 10% of the value of production comes from non-livestock farming activities." (Seré C., 1996)
Industrial systems: "Livestock systems where <10% of the dry matter fed to livestock is produced on the farm." (also known as Landless Livestock Production Systems (Seré C., 1996)

7. METHODOLOGY

This section presents the methodology for emission calculation, emission allocation and the emission intensity calculation. Methods for emission calculation of enteric fermentation and animal manure (direct and indirect) are given. Using this methodology the emissions for dairy and non-dairy cattle for both intensive and extensive production systems are calculated. Emissions from dairy cattle are then allocated partially to beef and partially to milk. All emissions from non-dairy cattle are allocated to beef. The emission intensities are then calculated by dividing the emissions for beef and milk by the production volumes of the respective product.

7.1 EMISSION CALCULATION

This section describes the method used to calculate the emissions from enteric fermentation and manure management. All emissions are calculated for: both intensive and extensive production systems, both dairy and non-dairy cattle on a global and regional level (25 regions).

CH_4 FROM ENTERIC FERMENTATION

CH_4 emissions are calculating using an altered version of eq. 10.21 from the IPCC guidelines. Instead of using gross energy intake from feed GE [MJ_{feed}/head*day] we use total gross energy intake from feed TGE [MJ_{feed}/yr] to get the total CH_4 emissions from enteric fermentation (EF) per type of animal. This alteration is due to the fact that the underlying data for this research is on a yearly basis.

$$Emissions_{EF}\left[\frac{kgCH_4}{yr}\right] = \frac{TGE\left[\frac{MJ_{feed}}{yr}\right] * Ym\left[\frac{MJ_{CH4}}{MJ_{feed}}\right]}{55.65\left[\frac{MJ_{CH4}}{kg_{CH4}}\right]} \tag{6}$$

Where the factor 55.65 is the energy content of methane, and Ym [5] is the cattle CH_4 conversion factor representing the "extent to which feed energy is converted to CH_4" (IPCC, 2006). TGE is calculated using:

$$TGE\ \left[\frac{MJ}{yr}\right] = TFEED\ \left[\frac{GgDM}{yr}\right] * 18.45\left[\frac{MJ}{kgDM}\right] * 10^6[\frac{kgDM}{GgDM}] \tag{7}$$

Where TFEED is the amount of feed for dairy/non-dairy cattle per year and 18.45 is a conversion factor for dietary gross energy intake per amount of dry matter, a relatively constant value (IPCC, 2006).

CH_4 FROM MANURE

The CH_4 from manure are calculated using the following equation:

$$Emissions_{manure}\left[\frac{kgCH_4}{yr}\right] = NRAN\ [head.yr] * ECH4ANWA[\frac{kgCH_4}{head.yr}] \tag{8}$$

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[5] Ym values used in this report are 3% for non-fibrous (food crops and animal products) and 6.5% for fibrous (residues, scavenging, grass & fodder).

Where NRAN is the number of living animals per year and ECH4ANWA is the amount of CH_4 emissions from animal waste per head per year.

N_2O FROM MANURE (DIRECT)

The direct N_2O emissions from manure can originate from manure managed in stables and manure deposited while grazing.

EMISSIONS IN STABLES & DURING GRAZING

The following 2 equations are used to calculate the direct N_2O emissions from manure (stables/grazing):

$$Emissions_{st/gr}\left[\frac{kgN_2O-N}{yr}\right] = IEF_{st/gr}\left[\frac{kgN_2O-N}{head.yr}\right] * NRAN\left[\frac{Mhead}{yr}\right] * 10^6\left[\frac{head}{Mhead}\right] \tag{9}$$

$$Emissions_{st/gr}\left[\frac{kgN_2O}{yr}\right] = Emissions_{st/gr}\left[\frac{kgN_2O-N}{yr}\right] * \frac{44}{28} \tag{10}$$

Where 44/28 is used for conversion of (N_2O-N) emissions to N_2O emissions (IPCC, 2006) and IEF is the implied emission factor for stables and grazing. The IEF is calculated by:

$$IEF_{st/gr}\left[\frac{kgN_2O-N}{head.yr}\right] = EF_{st/gr}\left[\frac{kgN_2O-N}{kgN}\right] * Frac._{st/gr} * NExcretion\left[\frac{kgN}{head.yr}\right] \tag{11}$$

Where EF is the respective emission factor from stables/grazing, $Frac._{st/gr}$ is the respective fraction of manure kept in stables/deposited while grazing and the Nitrogen excretion is the amount of Nitrogen excreted per animal per year.

As there is only data for the fraction of manure deposited while grazing, the fraction of manure kept in stables can be calculated using:

$$Frac._{gr} = 1 - Frac._{st} \tag{12}$$

N_2O FROM ANIMAL MANURE (INDIRECT)

The indirect N_2O emissions from manure can originate from soil leaching & runoff and volatilization.

LEACHING & RUNOFF

The following 2 equations are used to calculate the indirect N_2O emissions from leaching & runoff (IPCC, 2006 eq. 10.28 & 10.29):

$$\begin{aligned} Emissions_{l\&r}\left[\frac{kgN_2O-N}{yr}\right] \\ &= NExcretion\left[\frac{kgN}{head.yr}\right] * NRAN\left[\frac{Mhead}{yr}\right] * 10^6\left[\frac{head}{Mhead}\right] * EF_{l\&r} * Frac._{l\&r}\,[\%] \\ &* LEACHSOIL[\%] \end{aligned} \tag{13}$$

$$Emissions_{l\&r}\left[\frac{kgN_2O}{yr}\right] = Emissions_{l\&r}\left[\frac{kgN_2O-N}{yr}\right] * \frac{44}{28} \tag{14}$$

Where 44/28 is used for conversion of (N_2O-N) emissions to N_2O emissions (IPCC, 2006), $EF_{l\&r}$ is the emission factor for leaching & runoff[6], $Frac_{l\&r}$[7] is the fraction of managed manure nitrogen losses for livestock category due to runoff and leaching during solid and liquid storage of manure.(IPCC, 2006) and LEACHSOIL is the fraction of soils with leaching.

VOLATILIZATION

The following equation is used to calculate the indirect N_2O emissions from volatilization:

$$\begin{aligned} Emissions_{vol}\left[\frac{kgN_2O}{yr}\right] \\ &= NExcretion\left[\frac{kgN}{head.yr}\right] * NRAN\left[\frac{Mhead}{yr}\right] * 10^6\left[\frac{head}{Mhead}\right] * Frac._{vol}\,[\%] \\ &* EF_{vol}\left[\frac{kgN_2O-N}{kgNH_3-N+NO_x volatilised}\right] * \frac{44}{28} \end{aligned} \tag{15}$$

Where Frac. $_{vol}$ is fraction of managed manure nitrogen for livestock category that volatilises as NH3 and NOx in the manure management system and EF $_{vol}$[8] is emission factor for N2O emissions from atmospheric deposition of nitrogen on soils and water surface (IPCC. 2006).
Frac.$_{vol}$ is calculated by taking the median of the fractions from specific manure management system.

TOTAL EMISSIONS

The total amount of emissions can then be calculated using:

$$\begin{aligned} TEM[MtCO_2e] = \Big\{&(Emissions_{EF} + Emissions_{manure})\left[\frac{kgCH_4}{yr}\right] * GWP_{CH_4} \\ &+ \left(Emissions_{st/gr} + Emissions_{l\&r} + Emissions_{vol}\right)\left[\frac{kgN_2O}{yr}\right] * GWP_{N_2O}\Big\} \\ &* \ 10^{-9}\left[\frac{MtCO_2e}{kgCO_2e}\right] \end{aligned} \tag{16}$$

Where GWP_{CH4}= 25 and GWP_{N2O}=298. The share of emissions per emission source for both production systems are presented in appendix B.

7.2 EMISSION ALLOCATION

PHYSICAL ALLOCATION

The physical allocation method follows the IDF allocation approach that has also been adopted as a baseline approach from the CMWG. One difference that needs to be mentioned is that the IDF method uses *kg FPCM* as a functional unit and this analysis uses *kg milk* as this is the functional unit chosen by the consortium. However, the IDF allocation method is still applicable when assuming that all milk is standard (4% fat and 3.3% true protein) and adopting the IDF default allocation factors. The allocation factors for milk/beef are calculated using:

$$AF_{milk} = 1 - 6.04 * BMR \tag{17}$$

$$AF_{beef} = 1 - \ AF_{milk} \tag{18}$$

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[6] $EF_{l\&r}$ = 0.75% (IPCC, 2006 default)

[7] $Frac_{l\&r}$ = 30% (IMAGE default). *Note: Leaching in some countries is very low so 30% is a big factor, however it is taken as a default in order to stay consistent with the IMAGE model*

[8] EF $_{vol}$ = 1% (IPCC, 2006 default)

Where we take the default value of BMR, 0.02.

This results in AF_{milk}= 88% and AF_{beef}=12%. The total amount of emissions that are allocated to beef and milk can then be calculated using:

$$EM_{beef}\ [MtCO_2e] = TEM_{non-dairy}[MtCO_2e] + TEM_{dairy}[MtCO_2e] * AF_{beef} \tag{19}$$

$$EM_{milk}[MtCO_2e] = TEM_{dairy}[MtCO_2e] * AF_{milk} \tag{20}$$

Where TEM $_{non-dairy/dairy}$ is the total emissions calculated using the method presented in the previous section (7.1). All emissions are calculated for: both intensive and extensive production systems on a global and regional level (25 regions).

ECONOMIC ALLOCATION

Formula used for calculating the allocation factors in the economic approach is:

$$AF_{milk} = \frac{M_{milk} * Price_{milk}}{(M_{milk} * Price_{milk} + M_{beef} * Price_{beef})} \tag{21}$$

$$AF_{beef} = 1 - AF_{milk} \tag{22}$$

Where $M_{milk/beef}$ is the amount of milk/beef produced per year, and $Price_{milk/beef}$ are average prices per region, calculated by taking the 5 year average of prices [USD/tonne product] of all countries in the specific region.

Due to lack of data in FAOstat database, for calculating the economic allocation factors per region it is assumed that:

- Price of beef in USA, Canada and Greenland is the same as in OECD region
- Price of beef in Ukraine is the same as in other Easter Europe region
- Price of beef in the region Indonesia + is the same as in the SE Asia region
- Price of beef in Brazil is the same as in Rest of South America region
- Price of beef and milk in the World are averages of price of beef and milk from all regions

The total amount of emissions that are allocated to beef and milk can then be calculated using eq. 18 & 19 with AF_{milk} and AF_{beef} as defined by eq. 20 & 21. The economic allocation factors of milk and beef used in the analysis are given in appendix C, figure C.1. All emissions are calculated for: both intensive and extensive production systems and on a global and regional level (25 regions).

7.3 EMISSION INTENSITY

All emission intensities are calculated for: both intensive and extensive production systems on a global and regional level (25 regions).

BEEF EMISSION INTENSITY [KG CO_2E/KG CW BEEF]

The emission intensity of beef is calculated using:

$$EI_{beef}\left[\frac{kgCO_2e}{kgCWbeef}\right] = \frac{EM_{beef}[kgCO_2e]}{\{Prod.Vol.[kg\ CW\ beef] * FPSB_{ext/int}\}} \tag{23}$$

Where FPSB.$_{ext/int}$ is the fraction of beef produced with extensive/intensive production systems. This fraction is calculated using the following equation:

$$FPSB_{ext/int} = NRANS_{ext/int}[\frac{head}{yr}]/NRANS_{total}[\frac{head}{yr}] \tag{24}$$

Where NRANS is the number of cattle animals from extensive/intensive production systems slaughtered for meat.

MILK EMISSION INTENSITY [KG CO_2E/KG MILK]

The emission intensity of beef is calculated using:

$$EI_{milk}\left[\frac{kgCO_2e}{kgmilk}\right] = \frac{EM_{milk}[kgCO_2e]}{\{Prod.Vol.[kgmilk] * FPSM_{ext/int} * FCM_{ext/int}\}} \tag{25}$$

Where FPSM$_{ext/int}$ is the fraction of cow milk produced with extensive/intensive production systems and FCM$_{ext/int}$ is the fraction of cow milk out of the total milk[9] production. It is assumed that FPSM$_{ext/int}$ and FCM$_{ext/int}$ in IMAGE are equal to the ones provided by the GLEAM[10] model of FAOstat.

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[9] The value of the total amount of milk produced per year in IMAGE includes all types of milk (cow, goat, sheep, buffalo etc.)

[10] The GLEAM model distinguishes between grazing and mixed production systems for cattle. In this analysis grazing is extensive and mixed is intensive.

8. INPUT DATA

The table below outlines the type of data used to calculate the emission intensities.

Purpose	Type of data	Specifics	Source	Date
Total emissions	Number of animals	System: int/ext Cattle: dairy/non-dairy Region: 25 + World	IMAGE	2010
	CH_4 emissions - animal waste		EDGAR	2005
	Ym		IPCC	2006
	Feed for animals	System: int/ext Cattle: dairy/non-dairy Region: 25 + World	IMAGE	2010
	N excretion	Cattle: dairy/non-dairy Region: 25	IMAGE	2010
	Fraction manure in stables	System: int/ext Cattle: dairy/non-dairy Region: 25	IMAGE	2010
	Fraction deposited while grazing	System: int/ext Cattle: dairy/non-dairy Region: 25	IMAGE	2010
	EF stables/grazing	Region: 25	IMAGE	2010
	EF leaching & runoff		IPCC	2006
	Fraction leaching & runoff		IMAGE	2010
	Leach soils	Region: 25	IMAGE	2010
	Fraction volatilization		Calculated from IPCC values	2006
	EF volatilization		IPCC	2006
Allocation and Emission Intensities				
	Production volumes	Product: beef/milk Region: 25 + World	IMAGE	2010
	Number of slaughtered animals for meat	System: int/ext Region: 25 + World	IMAGE	2010
	% ext/int milk production	System: int/ext Region: 10 + World	GLEAM	2014
	% cow milk	Region: 10 + World	GLEAM	2014
	Price averages		FAOSTAT	

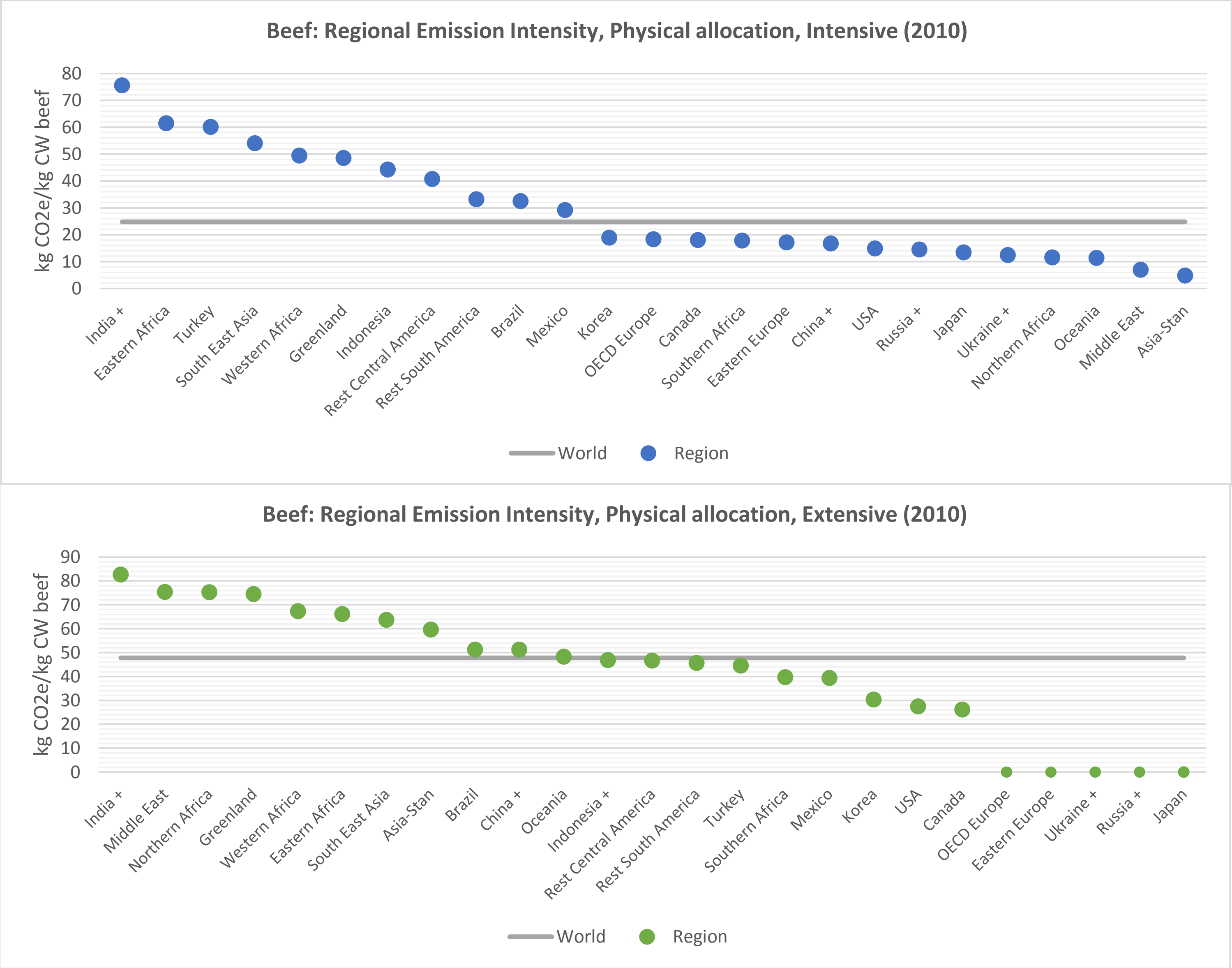
Table 2. Input data used for calculating the emissions intensities

9. RESULTS

This section presents the results of the calculated emission intensities. In addition, it highlights the best/ worst performing regions, the differences between the two production systems and outlines the exception cases. It should be noted that the emission intensities for extensive milk production in the regions OECD Europe, Eastern Europe, Ukraine+, Russia+ and Japan are 0 due to the fact that IMAGE modelling assumes no extensive milk production in those regions. They are presented as categories in the graph results for consistency.

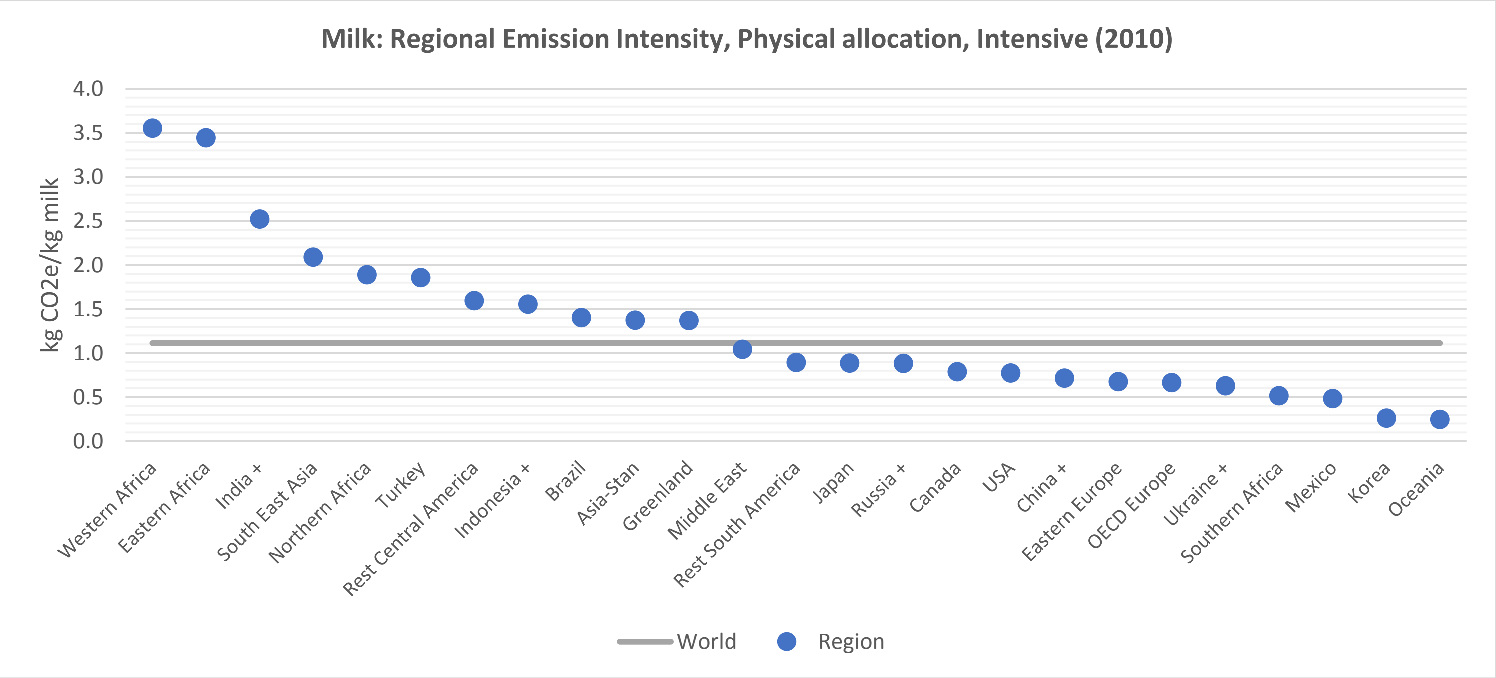
9.1 EMISSION INTENSITIES PHYSICAL ALLOCATION

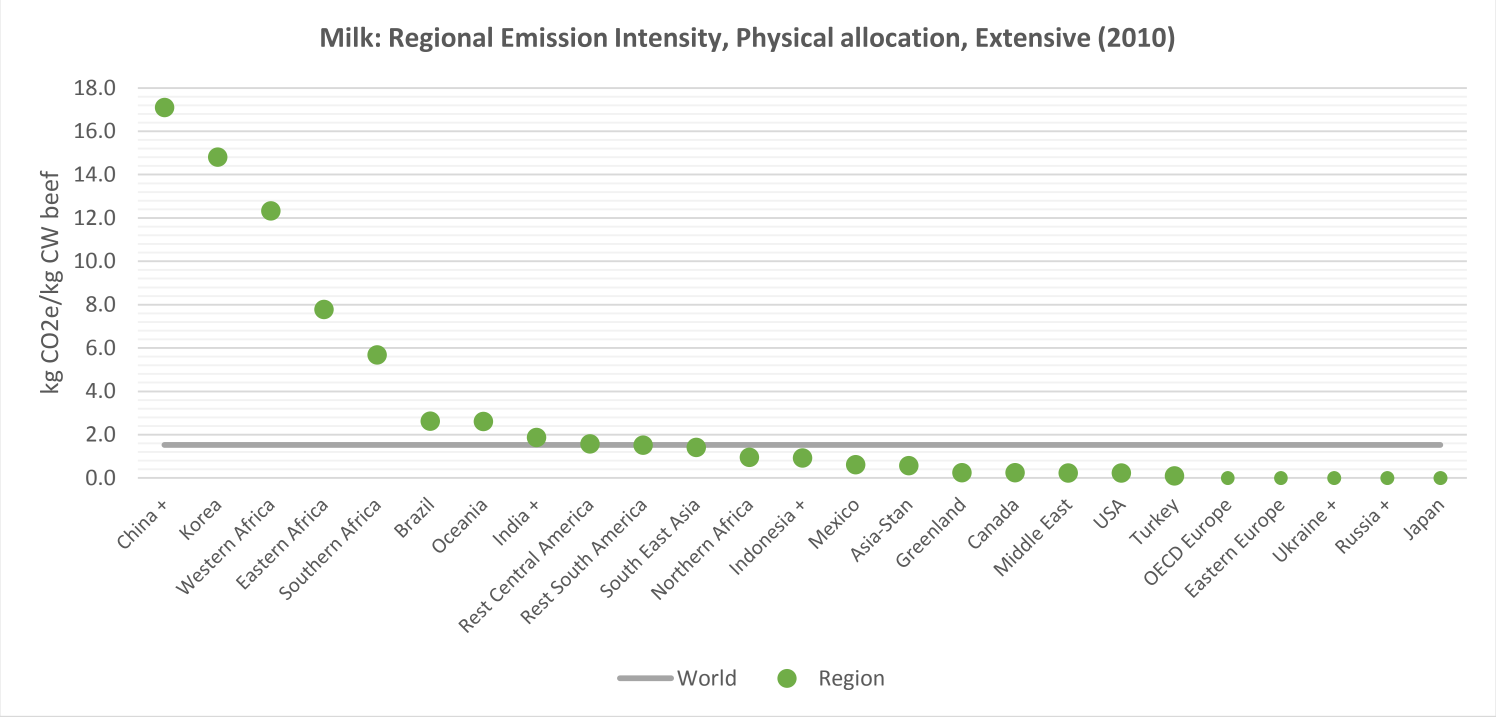
The following graphs (Figures 3 & 4) show the emission intensities for beef for the two production systems following the physical allocation. It can be seen that in both systems the region India + has the biggest emission intensity (75.6 & 82.6 kg CO_2e/kg CW beef). The region Asia-Stan performs best for intensive (4.8 kg CO_2e/kg CW beef) and Canada for extensive (26.2 kg CO_2e/kg CW beef).



Figures 3 & 4. Results for beef emission intensities using the physical allocation method

Figures 5 & 6 show that Western Africa for intensive (3.6 $kgCO_2e/kg$ milk) and China+ for extensive (17.1 $kgCO_2e/kg$ milk) are the worst performing ones for milk emission intensities using physical allocation. The best performing ones are Oceania (0.2 $kgCO_2e/kg$ milk) for intensive and Turkey (0.1 $kgCO_2e/kg$ milk) for extensive. When looking at the results from extensive milk production a few very high values are spotted (China+, Korea, Western Africa, Easter Africa and Southern Africa). These high values are mainly due to the low amounts of milk produced by extensive systems in these regions [11].


Milk: Regional Emission Intensity, Physical allocation, Intensive (2010)


Milk: Regional Emission Intensity, Physical allocation, Extensive (2010)

Figures 5&6. Results for milk emission intensities using the physical allocation method

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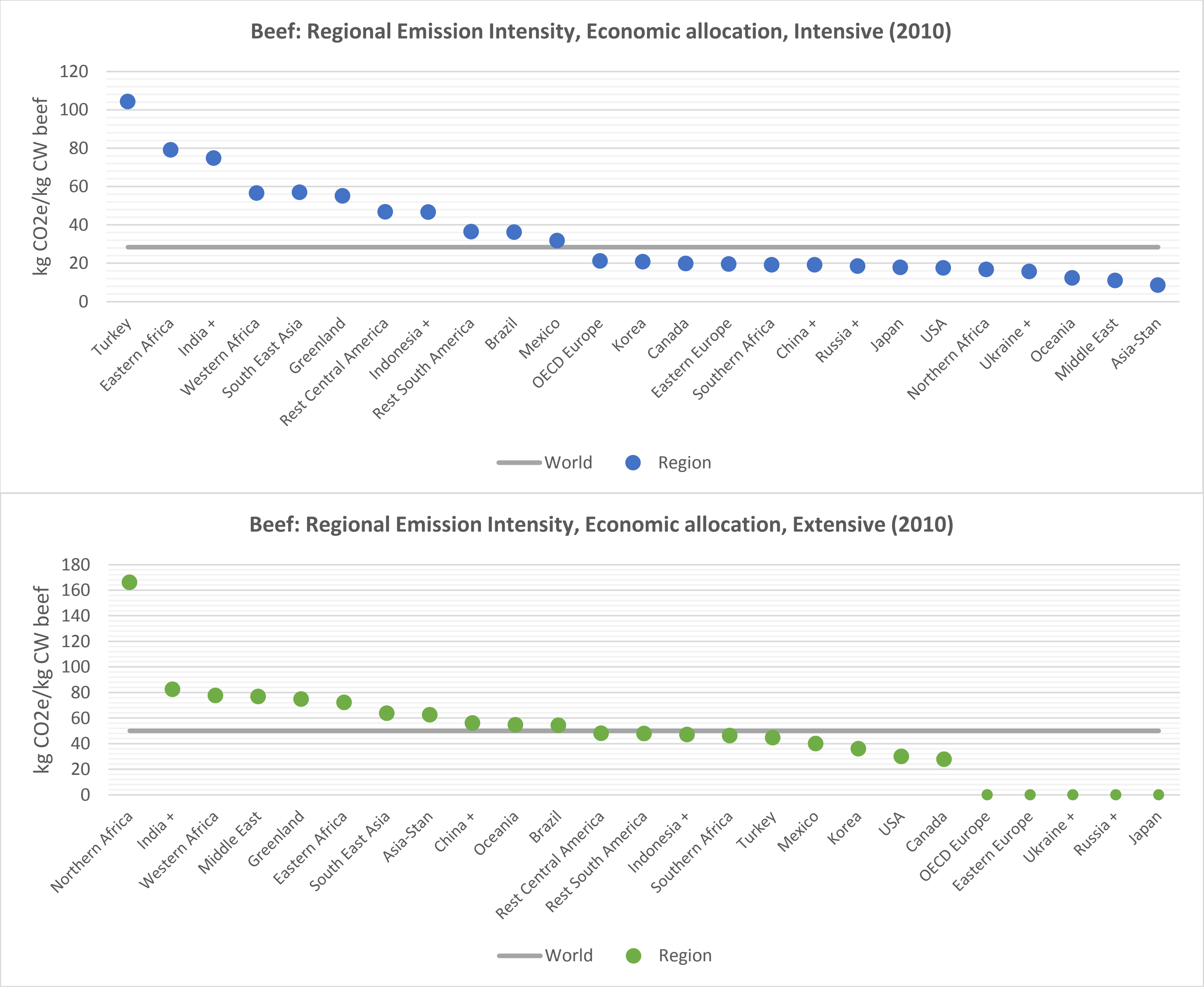
[11] These percentage shares ($FPSM_{ext/int}$) are assumed to be equal to the ones provided by the GLEAM model of FAOstat. There might be some discrepancy between emission values calculated using IMAGE data and shares of cow milk produced that is adopted from FAOstat.

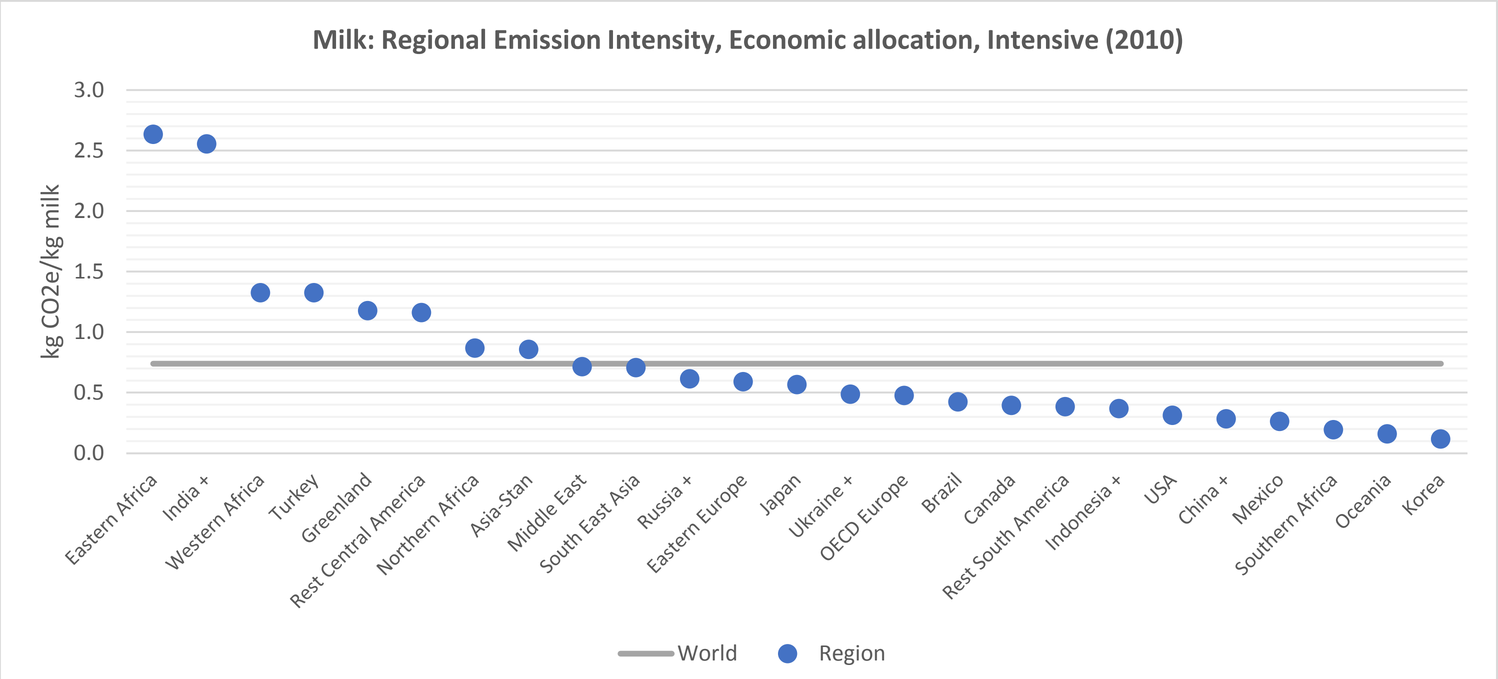
9. 2 EMISSION INTENSITIES ECONOMIC ALLOCATION

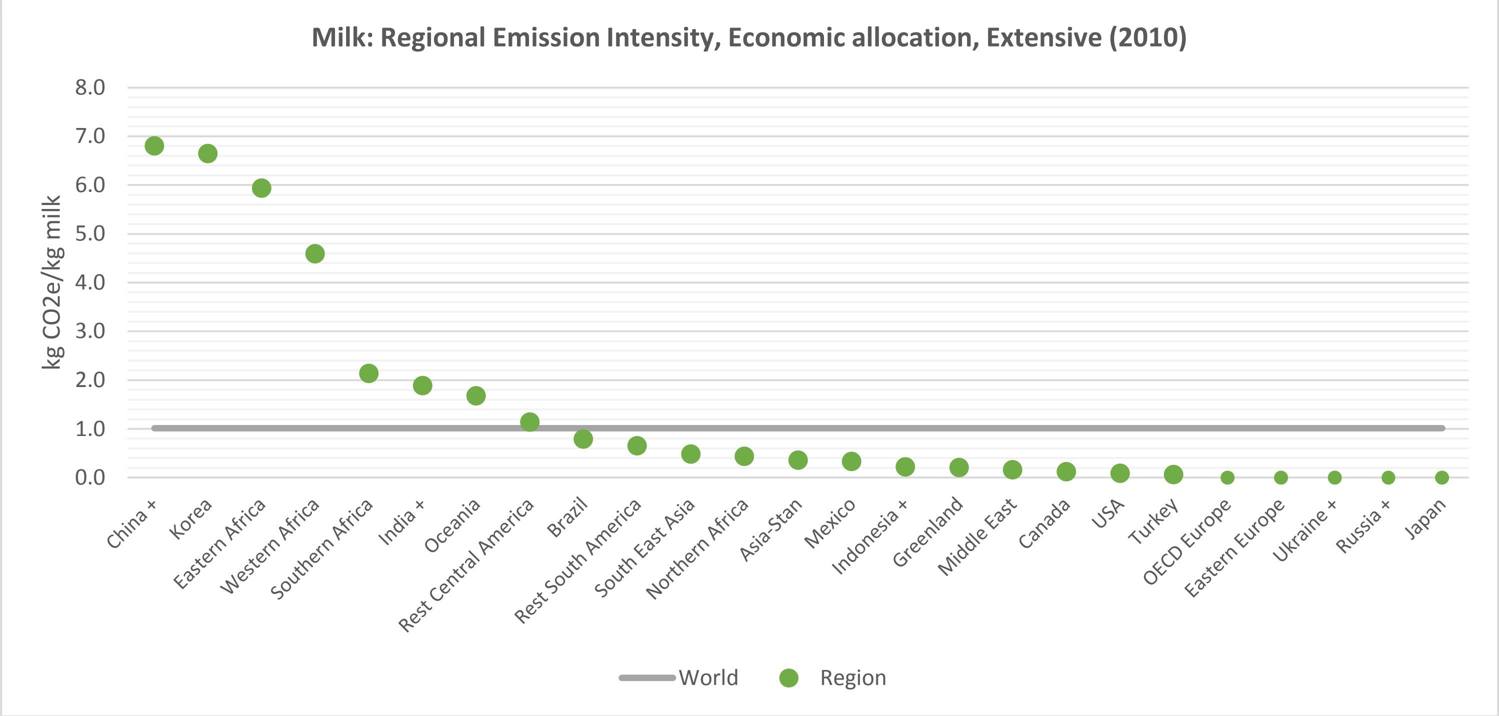
The following graphs (Figures 7 & 8) present the emission intensities for beef for the two production systems following the economic allocation. It can be seen that the worst performing ones are Turkey for intensive (104.3 kgCO_2e/kg CW beef) and Northern Africa for extensive (166.1 kgCO_2e/kg CW beef). Northern Africa scores nearly double from the second worst (India+) and this is primarily due to the fact that the calculated emissions from dairy cattle extensive are much higher than emissions from non-dairy cattle extensive for North Africa; meaning that emission intensity is increased to a greater extent when AF beef is greater (which is the case in economic allocation). The region Asia-Stan performs best for intensive (8.6 kgCO_2e/kg CW beef) and Canada for extensive (27.8 kgCO_2e/kg CW beef) (same as the results from physical allocation).



Figures 7&8. Results for beef emission intensities using the economic allocation method

Figures 9 & 10 show that Eastern Africa for intensive (2.6 kgCO_2e/kg milk) and China+ for extensive (6.8 kgCO_2e/kg milk) are the worst performing ones for milk emission intensities using economic allocation. Eastern Africa and India+ (the second worst performing) scores nearly double from the third worst. This is mainly due to a combination of high emissions and big economic allocation factors. The best performing ones are Korea for intensive (0.1 kgCO_2e/kg milk) and Turkey for extensive (0.1 kgCO_2e/kg milk). Similar to the results from physical allocation, when looking at the results from extensive milk production a few very high values are spotted (China+, Korea, Western Africa, Easter Africa and Southern Africa). The reason for this is mainly the low amounts of milk produced by extensive systems in these regions (see footnote 11).





Figures 9&10. Results for milk emission intensities using the economic allocation method

For beef, the extensive production system is generally more emission intense with certain cases of exception. Namely:

- Turkey (both physical and economic allocation): Emission intensities of intensive production system are higher than the ones of extensive because IMAGE data shows that in 2010 a small percentage of cattle in intensive production system are slaughtered for beef (compared to extensive production system cattle slaughtered for beef).
- Eastern Africa (economic allocation): Emission intensities of intensive production system are higher than the ones of extensive because IMAGE data shows that in 2010 a small percentage of cattle in intensive production system is slaughtered for beef (compared to extensive production system cattle slaughtered for beef).

For milk, the intensive production system is more emission intense for the following regions: Canada, USA, Rest of Central America, North Africa, Turkey, Asia-Stan, Middle East, India, South East Asia, Indonesia and Greenland. This is due to a combination of higher emission intensities from the intensive production system and a low amount of cow milk produced by the means of intensive production systems. In China and Korea, on the other hand, extensive production systems for milk have much higher emission intensities as only a small amount of cow milk is produced by extensive systems (only 4%).

9.3 PHYSICAL VS. ECONOMIC ALLOCATION METHOD

In general more emissions are allocated to beef and less to milk when using economic allocation. Thus, the economically allocated beef emission intensities are higher and the milk ones lower when compared to the physically allocated emission intensities (Figure 11).

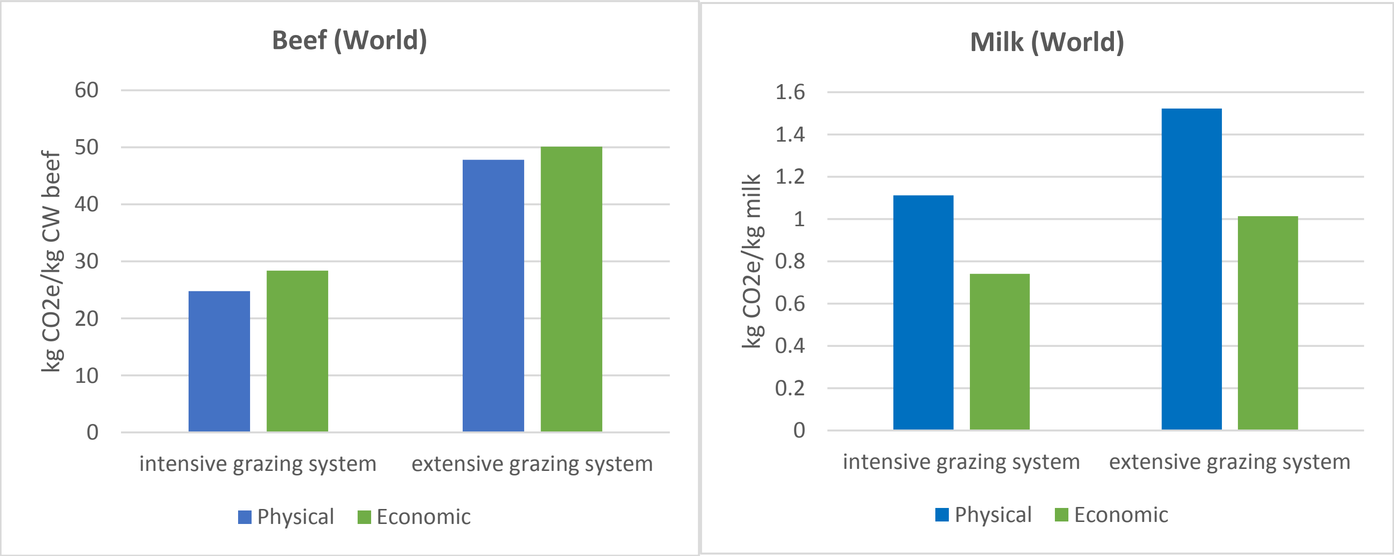


Figure 11. Comparison between the physically and economically calculated emission intensities of beef and milk for intensive and extensive production systems on a global level

It was calculated that the average absolute percentage changes between the physically and economically calculated emission intensities for beef are 21% (intensive) and 10% (extensive). The average absolute percentage changes for milk are 43% (intensive) and 38% (extensive) (See appendix D for more regional details). Milk emission intensities experience a greater difference as in this analysis milk has beef as a co-product; while beef has no co-products (see section 5.2).

10. DISCUSSION

10.1 RESULTS

Tables 3 & 4 present a comparison between the results from this analysis and results from external literature. Comparison of the results with other literature is not straightforward as the scope and aim of this project are specifically designed for the SBT. When comparing the results it should be kept in mind that there are fundamental differences between the studies, namely:

- Emission scope - Most LCAs have a wider emission scope which result in up to 50% higher emission intensities in some regions (e.g. physical allocation of milk on a global level with a cradle-farm gate scope (Gerber, 2013)). In tables 3 & 4 the emission scope is stated for each study. The next section offers a more extensive discussion on emission scopes and their implication on the emission intensities of beef and milk.
- Geographical scope – Some studies have a smaller geographical scope, for instance single EU countries or sub-regions of a country such as western Canada or Southern Brazil. Single countries from the EU are compared with results from the whole OECD region, the study of (Karen A. Beauchemin, 2010) is compared with results from Canada, the study of (Milene Dick, 2015) is compared with the results from Brazil, and the study of (Stephen Wiedemann, 2014) is compared with the results from Oceania. This may lead to inconsistency with the results.
- Functional units - Studies differ in their chosen functional units: kg beef only accounts for the meat, kg carcass weight (CW) beef includes the bones, and kg live weight (LW) beef consists of the whole animal including the bones and internal organs. For instance CW is in general 58% of LW (J.P. Lesschen, 2011). A functional unit of kg LW beef would lead to lower emission intensities than a functional unit of kg beef or kg CW beef (e.g. physical allocation of beef in Brazil (Milene Dick, 2015)).
- Production systems analysed - Not all studies distinguish between the two systems of production, thus single results include emissions and production volumes from both systems (e.g. (Karen A. Beauchemin, 2010)).
- GWP used - The GWP of N_2O and CH_4 varies from 298-310 and 21-25 respectively through the studies resulting in variations in results.

In general the results are in the same ranges as the rest of the literature when the abovementioned points are considered.

Physical allocation					
Source *(Scope)*	**Region**	**Beef**		**Beef (Ecofys) (kg CO$_2$e/kg CWbeef)**	
		Intensive	**Extensive**	**Intensive**	**Extensive**
(Karen A. Beauchemin, 2010)*(C-FG)*	W. Canada	22 kgCO$_2$e/kg CW beef		18.1	26.2
(Opio, 2013)*(C-ret.)*[12]	Global	46.2 kgCO$_2$e/kg CW beef		24.8	47.8
(Milene Dick, 2015)*(C-FG)*	S. Brazil	9.16 kgCO$_2$e/kg LW beef	22.52 kgCO$_2$e/kg LW beef	32.6	51.3
(Food and Agriculture Organization of the UN, 2010)*(C-ret)*	Global	20.2 kgCO$_2$e/kg CW beef (beef cattle); 15.6 kg CO$_2$e/kg CW beef(dairy cattle)		24.8	47.8
(European Commission-JRC, 2010)*(C-FG)*	27 EU	22.2 kgCO$_2$e/kg beef		18.4	n.a.
(Gerber, 2013)*(C-FG)*	Global	56.2 kgCO$_2$e/kg CW beef	102.2 kgCO$_2$e/kg CW beef	24.8	47.8
(Thibault Salou, 2014)*(C-FG)*	France	11.4 kgCO$_2$e/kg LW beef		18.4	n.a.
(Stephen Wiedemann, 2014)*(C-FG)*	Australia	15 kg CO$_2$e/kg beef		11.4	48.3
(Raymond L. Desjardins D. E., 2012)*(C-FG)*	USA	13-19.2 kgCO$_2$e/kg LW beef		15.0	27.5
(Raymond L. Desjardins D. E., 2012)*(C-FG)*	Brazil	22.4 kg CO$_2$e/kg LW beef		32.6	51.3
Source *(Scope)*	**Region**	**Milk**		**Milk (Ecofys) (kg CO$_2$e/kg milk)**	
		Intensive	**Extensive**	**Intensive**	**Extensive**
(Opio, 2013)*(C-ret)*	Global	2.8 kgCO$_2$e/kg FPCM		1.1	1.5
(Food and Agriculture Organization of the UN, 2010)*(C-ret)*	Global	2.4 kg CO$_2$e/kg FPCM		1.1	1.5
(European Commission-JRC, 2010)*(C-FG)*	27-EU	1.4 kg CO$_2$e/ kg raw milk		0.7	n.a.
(Gerber, 2013)*(C-FG)*	Global	2.6 kg CO$_2$e/kg FPCM	2.9 kg CO$_2$e/kg FPCM	1.1	1.5
(Thibault Salou, 2014)*(C-FG)*	France	0.9 kgCO$_2$e/kg FPCM		0.7	n.a.
(Greg Thoma, 2013)*(C-G)*	USA	1.77 -2.4 kg CO$_2$e/kg milk		0.8	0.2

Table 3. Overview of results using physical allocation from this analysis and external literature

Economic allocation					
Source *(Scope)*	**Region**	**Beef**		**Beef (Ecofys) (kg CO$_2$e/kg CWbeef)**	
		Intensive	**Extensive**	**Intensive**	**Extensive**
(Blonk, 2008)*(C-G)*	Netherlands	8.9 kgCO$_2$e/kg beef (dairy cattle); 15.9 kgCO$_2$e/kg beef (beef cattle)		21.2	n.a.
(Thibault Salou, 2014)*(C-FG)*[13]	France	9.44 kgCO$_2$e/kg LW beef		21.2	n.a.
(Stephen Wiedemann, 2014)*(C-FG)*	Australia	22 kg CO$_2$e/kg beef		12.3	54.8
Source *(Scope)*	**Region**	**Milk**		**Milk (Ecofys) (kg CO$_2$e/kg milk)**	
		Intensive	**Extensive**	**Intensive**	**Extensive**
(M.A. Thomassen, 2008)*(C-FG)*	Netherlands	1.4 kg CO$_2$e/kg FPCM (conventional); 1.5 kg CO$_2$e/kg FCPM (organic)		0.5	0
(Broekema, 2014)*(C-G)*[14]	Netherlands	1.12 kg CO$_2$e/kg semi-skimmed milk		0.5	0
(Thibault Salou, 2014)*(C-FG)*	France	1.05 kgCO$_2$e/kg FPCM		0.5	0

Table 4. Overview of results using economic allocation from this analysis and external literature

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[12] C-ret: Cradle - retail

[13] C-FG:Cradle – farm gate

[14] C-G: Cradle - grave

10.2 EMISSION SCOPE

The results from this analysis do not represent the whole supply chain of the commodities beef and milk. This analysis focused only on the non-CO_2 on-farm emissions. As narrow as this scope might seem, figure 12 below shows that on a *global level* these on-farm emissions constitute 47.6% (beef) and 55.7% (milk) from the total supply chain emissions. However, it is important to bear in mind that feed production and fertilizer use for feed are big contributors to the total amount of emissions (~35%) (Gerber, 2013). In addition, LUC emissions are approximately 15.4% for beef and 0.7% for milk (Gerber, 2013). Thus the *global* results of this analysis should be evaluated, compared or used with the approximation that only about 50% of the whole supply chain emissions for beef and milk are taken into account.

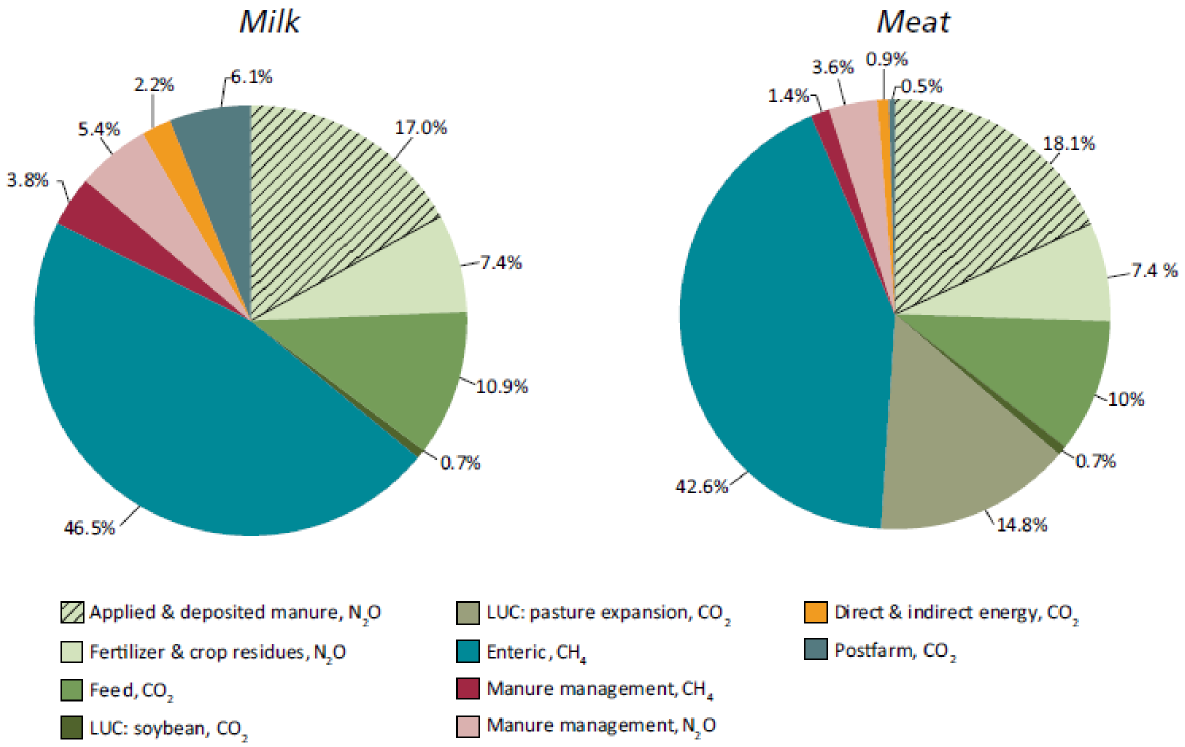

Figure 12. Global emissions from cattle milk and beef supply chains by emission type (Gerber, 2013)

Supply chains differ regionally, and thus separate supply chain processes can have a different effect on the emission intensities of the products. These regional differences can be seen in figures 13 & 14. While figure 13 shows that enteric fermentation has a great share in all regions (in Sub-Saharan Africa and South Asia even more than 50%) it can also be seen that LUC emissions from pasture expansion constitute to one third of the emissions in Latin America and the Caribbean. Applied and deposited manure for fed production has a relatively big share and constitutes to almost a third in most regions. Feed production constitutes to almost 10% of beef emission intensity in South Asia. Enteric fermentation and applied and deposited manure emissions are also dominant parts in milk emissions in all regions while CH_4 emissions from manure management constitute to almost one fourth of the emissions in North America (Figure 14). It can also be seen that CO_2 emissions from on-farm energy use have greater effects in some regions than other, and generally are more prominent in the milk emissions. To summarize, when evaluating the emission scope of this analysis it is important to take in mind that the dominant supply chain processes differ regionally.

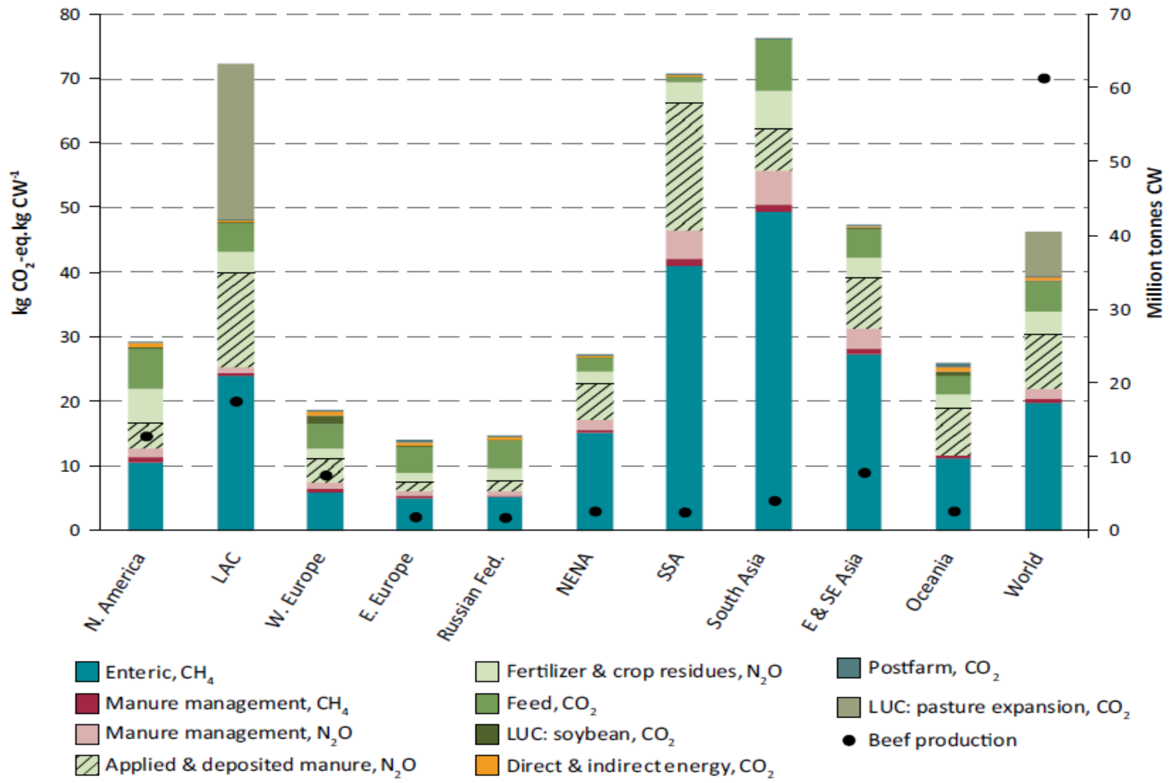

Figure 13. Regional variation in beef emission intensity and the respective contributions of the supply chain processes and regional variation in beef production (Gerber, 2013)[15]

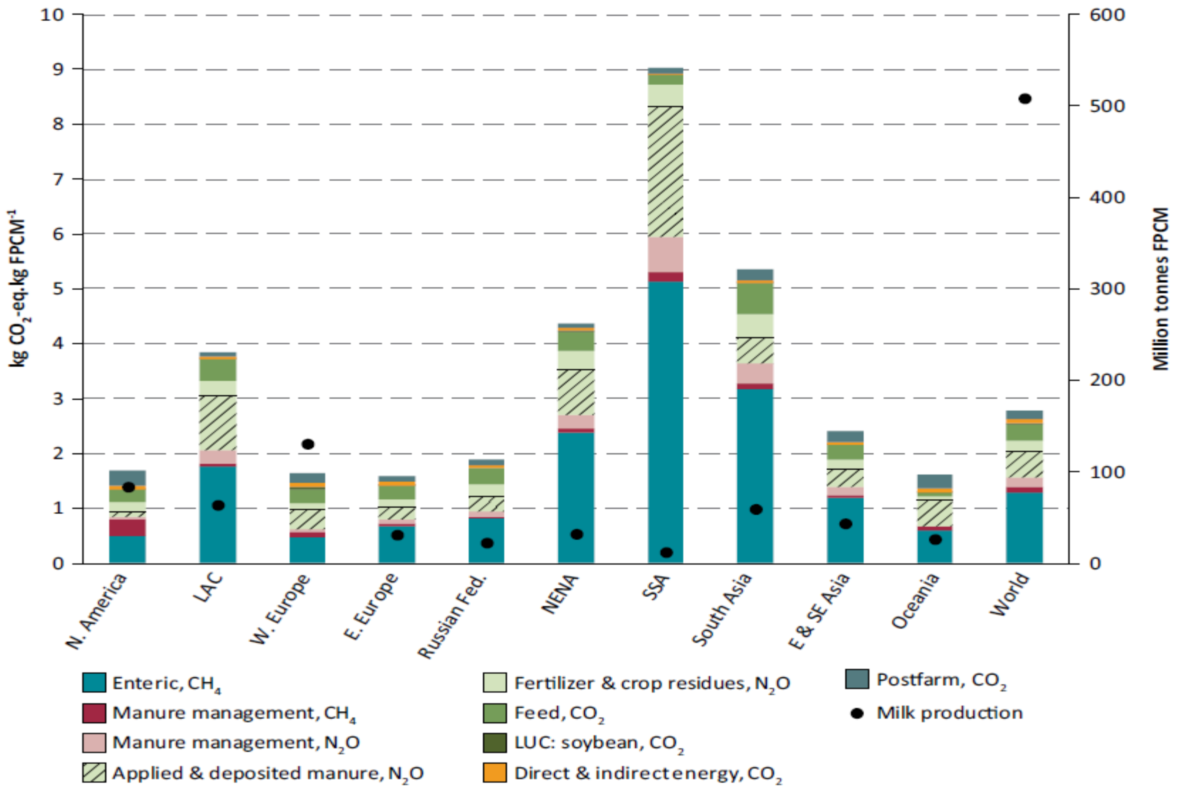

Figure 14. Regional variation in beef emission intensity and the respective contributions of the supply chain processes and regional variation in beef production (Gerber, 2013)

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[15] LAC: Latin America and the Caribbean; NENA: Near East and North Africa; SSA: Sub-Saharan Africa

10.3 METHODOLOGICAL CHOICES & RECOMMENDATIONS

In literature, the economic allocation approach is the most often used one. This is mainly due to: lack of other data or scientific knowledge and convenience due to availability of economic data (John Reap, 2008). While being very convenient, the very essence of this approach can be questioned as it uses only economic value as an indicator for allocation. Economic value usually is not easily related to environmental burdens and it can lead to either over-allocation or under-allocation to co-products. In addition, economic value is temporally and spatially variable as it is market based. The economic value of products can be influenced by local, regional and global markets leading to variations in producer prices, wholesale prices and import/export. This raises the question whether allocating the environmental burdens to products should be singularly market influenced. The level of credibility that the usage of different prices would bring to the analysis is a point that asks for further research.

Physical allocation, on the other hand, is much more data and scientific knowledge demanding (John Reap, 2008). This complexity constitutes the main drawback of the approach. Details on the complexity of creating a physical allocation methodology can be found in the study by Thoma et al. (Thoma, 2013). The main advantages and supporting factors for this choice of allocation method are:

- In line with the ISO 14044 standards;
- Reflects the underlying use of feed energy by the dairy animals and the physiological feed requirements of the animal to produce beef and milk;
- The main factor in determining the amount of CH_4 emissions from enteric fermentation and the CH_4 and N_2O emissions from animal manure is the feed consumption by animals (fits the emission scope of the analysis).

When comparing the results from the physical and economic allocation a great difference in results is outlined. The average differences are 16% and 40% for beef and milk respectively. Milk emission intensities experience a greater difference as in this analysis milk has beef as a co-product; while beef has no co-products. These differences quantify the big importance of choosing the right allocation method and the vulnerability of the final results.

In general, when analysing edible co-products (e.g. chicken and egg, goat milk and meat) the same reasoning applies. Avoiding allocation is difficult due to the need of system expansion or subdivision (almost impossible to find fitting alternative ways of production). Economic approach is simple, but too market based. Physical allocation is more data intensive, however reflects the underlying use of feed energy to produce the edible products.

Throughout the analysis a few assumptions were made. The analysis assumes that the cattle CH_4 conversion factor Ym [MJ_{CH4}/MJ_{feed}] is 3.0% for non-fibrous feed (incl. food crops and animal products) and 6.5% for fibrous crops (incl. residues, scavenging and fodder). These values are default IMAGE values and are used in the analysis due to consistency in methodologies. The values are also given by the IPCC guidelines (IPCC, 2006) as defaults with an uncertainty range of ±1%. Using these two general values can be considered as an oversimplification, as the types and quality of feed and with that the CH_4 conversion factor can vary significantly on a local and regional scale (IPCC, 2006). As enteric fermentation emissions constitute a great part of the on-farm emissions of cattle further research on estimating more concrete CH_4 conversion factors per feed type and region is needed.

The leaching and runoff fraction is assumed to be 30% in all regions, which is the default value in IMAGE calculations. The reason for taking this assumption is to stay consistent with the methodology for emission calculation in IMAGE. This value is proposed as a default value by the IPCC (IPCC, 2006) with a range of uncertainty of 0.1-0.8. The IPCC however, does state that this value only applies to “regions where soil water-holding capacity is exceeded, as a result of rainfall and/or irrigation (excluding drip irrigation), and leaching/runoff occurs” and for other regions the default factor should be 0 (IPCC, 2006). It is important to note that assuming the 30% leaching and runoff fraction for all regions is a rigorous assumption, however it does not skew the results to a significant extent as the percentage share of leaching and runoff emissions out of the total emissions per regions is only 0.2 % -1.67%.

The analysis assumes that all milk is standard (3.3% fat and 4% protein). For the purpose of this analysis this assumption is valid as it is on a very aggregate level and the regional emission intensities are still correct relative to one other. However, it is important to note that the quality of the milk can vary even on a farm level. Thus, when conducting a similar analysis on a more detailed level it is recommended to use the specific quality of the milk and adopt kg FPCM as a functional unit.

The analysis does not take into account the emissions from animals that died throughout 2010. This is due to the lack of data on number of dead animals in IMAGE. The effect of this exclusion requests further research. In relation to this, the recommendations for data improvement for a better application of the IMAGE model in this type of analysis are the following:

- Data for emissions per type of animal
- Data for emissions per type of production systems
- Data for FPCM of milk per region (so no default factor is needed for the physical allocation)

In addition to this, the extensive milk production in OECD Europe, Eastern Europe, Ukraine+, Russia+ and Japan is a point of further improvement of this analysis. It should be looked into more details whether IMAGE data can be improved or external data should be used. Lastly, the shares of milk produced by intensive/extensive should be modelled in order to increase the data consistency, results credibility and deal with the outlier regions in the results of extensive milk production (China and Korea).

10.4 MOVING FORWARD WITH CONSTRUCTING THE EMISSION INTENSITY PATHWAYS TO 2050

The following table (table 5) points out the type of data needed/missing to create the emission intensity pathways to 2050. For obtaining data projections to 2050 the IMAGE model uses either the scenario RCP 2.6 (Representative Concentration Pathway) or the SSP2.450 (Shared Socioeconomic Pathway). Both of these scenarios have a high potential of staying below the 2°C target by 2100 which makes them applicable for constructing the emission intensity pathways.

Type	Data available	Data needed
Enteric Fermentation	- Feed for animals - Ym	
Animal waste CH4	- Number of animals	- Emissions from animal waste to 2050
N2O direct	- Number of animals	- N excretion 2050 - Fraction manure in stables - Fraction deposited while grazing - EF stables/grazing
N2O indirect leaching & runoff	- Number of animals	- N excretion 2050 - EF l&r - Fraction l&r - Leach soils
N2O indirect vol.	- Number of animals	- N excretion 2050 - Fract. volatilization
Physical allocation	- Production volumes - Ext/int production %	- % ext/int production - % cow milk
Economic allocation	- Production volumes - Ext/int production %	- Price projections - % ext/int production - % cow milk

Table 5. Type of data available/missing to create the emission intensity pathways to 2050

11. CONCLUSION

When calculating the emission intensities of beef and milk emissions from dairy cattle were allocated partially to beef and partially to milk. All emissions from non-dairy cattle were allocated to beef. In this analysis both economic and physical allocation was used. In general more emissions are allocated to beef and less to milk when using economic allocation. Thus, the economically allocated beef emission intensities are higher and the milk ones lower when compared to the physically allocated emission intensities. For beef, the extensive method is generally more emission intense with certain cases of exception, while this rule does not hold for milk.

With physical allocation for beef the worst performing region is India+ (75.6 & 82.6 kg CO2e/kg CW beef). The region Asia-Stan performs best for intensive (4.8 kg CO2e/kg CW beef) and Canada for extensive (26.2 kg CO2e/kg CW beef). With physical allocation for milk the worst performing regions are Western Africa for intensive (3.6 kgCO2e/kg milk) and China+ for extensive (17.1 kgCO2e/kg milk). The best performing ones are Oceania (0.2 kgCO2e/kg milk) for intensive and Turkey (0.1 kgCO2e/kg milk) for extensive.

With economic allocation for beef the worst performing regions are Turkey for intensive (104.3 kgCO2e/kg CW beef) and Northern Africa for extensive (166.1 kgCO2e/kg CW beef). The region Asia-Stan performs best for intensive (8.6 kgCO2e/kg CW beef) and Canada for extensive (27.8 kgCO2e/kg CW beef) (same as the results from physical allocation). With economic allocation for milk the worst performing regions are Eastern Africa for intensive (2.6 kgCO2e/kg milk) and China+ for extensive (6.8 kgCO2e/kg milk). The best performing ones are Korea for intensive (0.1 kgCO2e/kg milk) and Turkey for extensive (0.1 kgCO2e/kg milk).

This study recommends using physical allocation when analysing beef and milk or edible animal co-products in general. This is mainly because: avoiding allocation is difficult due to the need of system expansion or subdivision (almost impossible to find fitting alternative ways of production) and economic allocation while being simple is too market based. Physical allocation is more data intensive, however reflects the underlying use of feed energy to produce the edible products.

Further research needs to be conducted on estimating more concrete CH4 conversion factors per feed type and region and the effect of exclusion of dead animals. In order to improve the results from this analysis data should be improved and updated, namely it should include: data for extensive milk production in OECD Europe, Eastern Europe, Ukraine+, Russia+ and Japan, data for the shares of milk produced by intensive/extensive systems, data for regional leaching & runoff factors.

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APPENDIX A

EMPIRICAL RELATIONSHIP OF PHYSICAL ALLOCATION

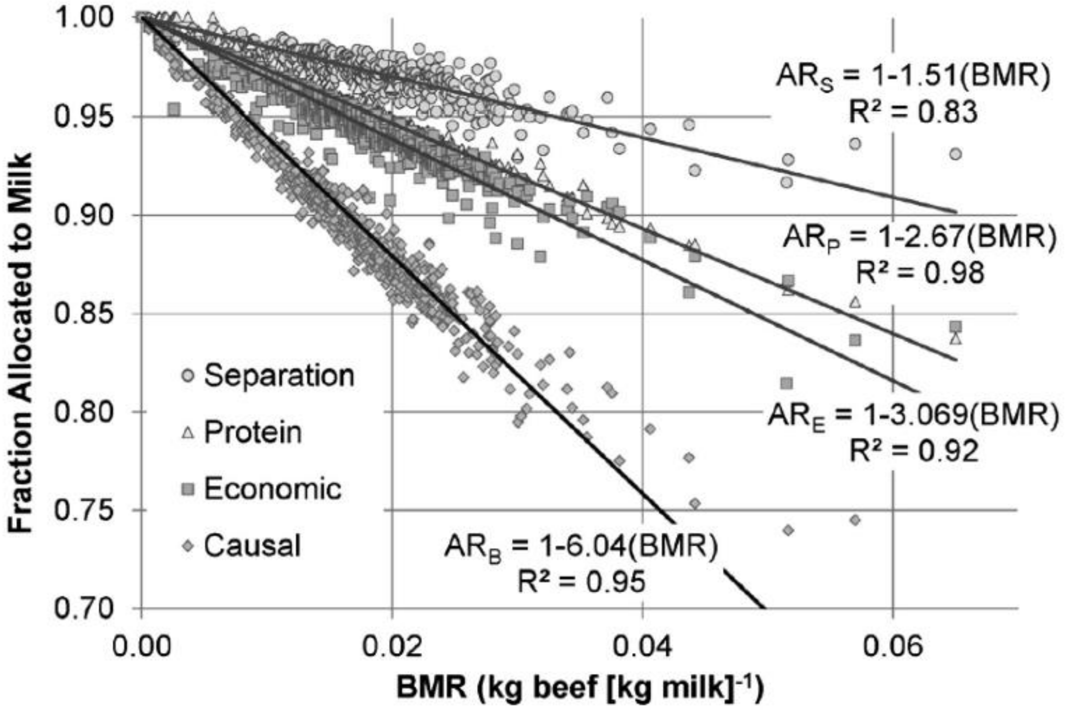

Figure A.1. Fraction allocated to milk as a function of beef-milk ratio for several allocation choices. The empirical relationship used in the analysis from the causal allocation choice is shown. (International Dairy Federation, 2015)

APPENDIX B

EMISSION BREAKDOWN

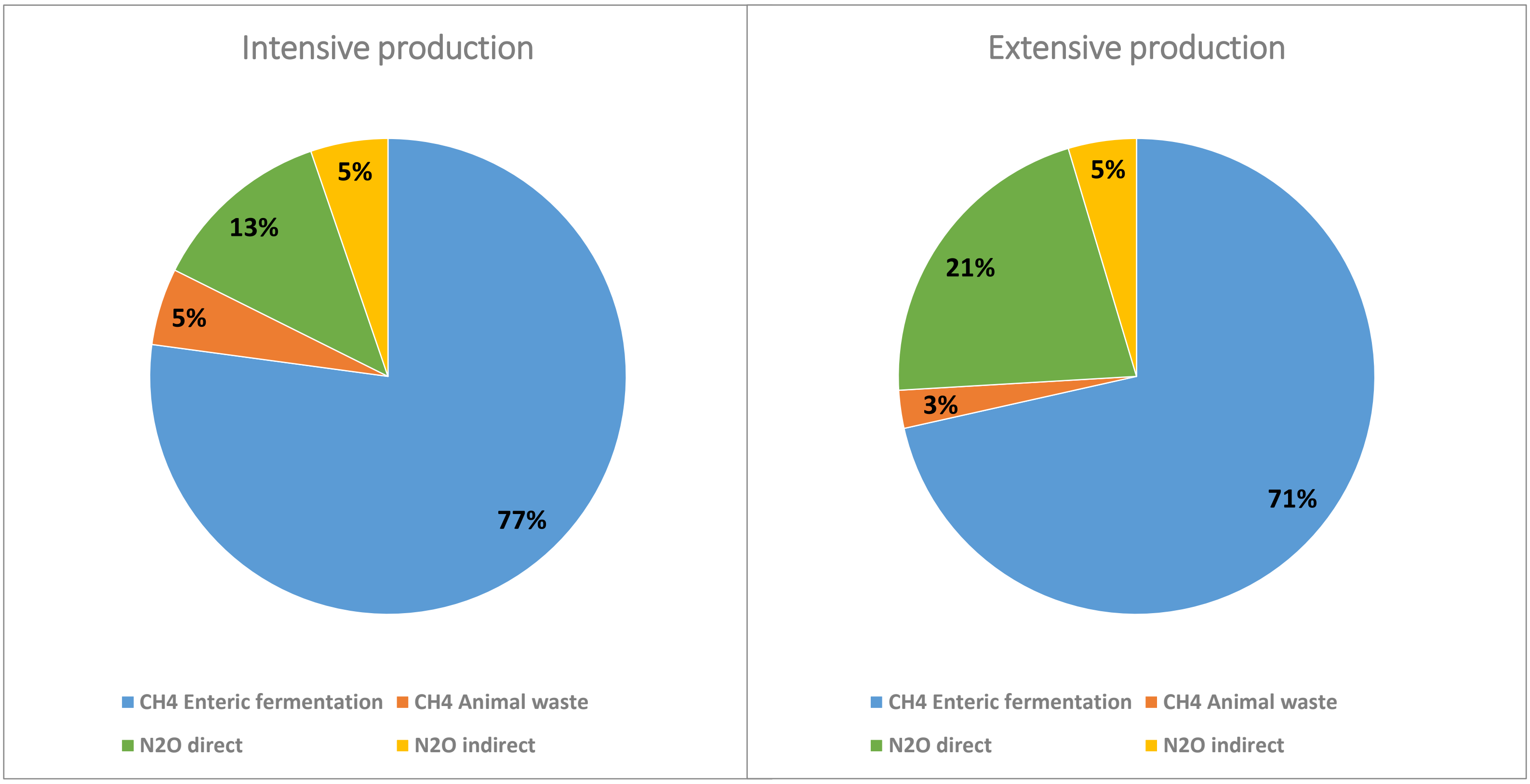

Figure B.1. & B.2. Emission breakdown per emission category in 2010 for the two production systems

APPENDIX C

ALLOCATION FACTORS FOR ECONOMIC ALLOCATION

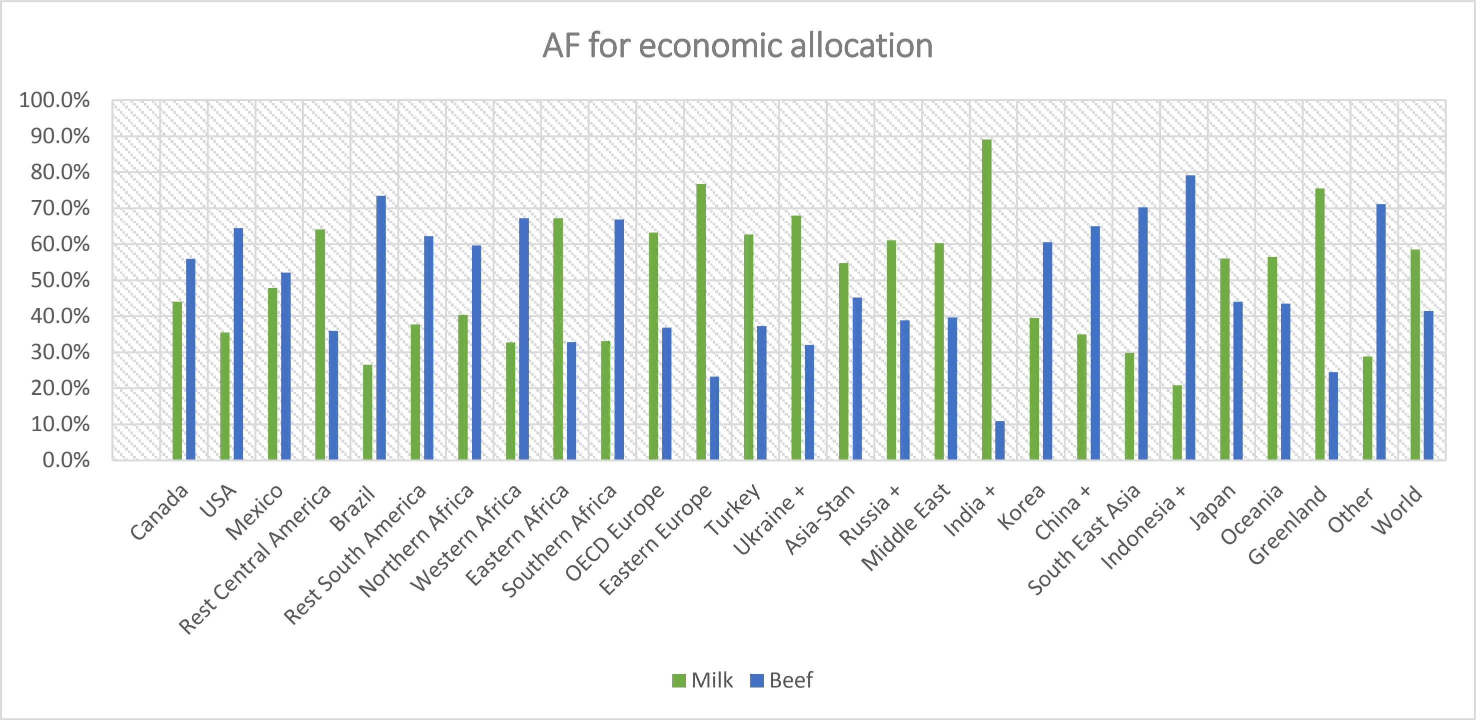

Figure C.1. Economic allocation factors for milk and beef

APPENDIX D

SENSITIVITY ANALYSIS

In order to quantify the impact of using different allocation methodologies a sensitivity analysis is performed. The sensitivity analysis calculates the absolute percentage change in emission intensity for beef and milk ext/int production systems when using the physical and economic allocation method relative to the physical emission intensities. The following equation is used:

$$Abs.\%Change_{beef/milk}[\%] = \left| \frac{EI(Physical)_{beef/milk} - EI(Economic)_{beef/milk}}{EI(Physical)_{beef/milk}} \right| \qquad (26)$$

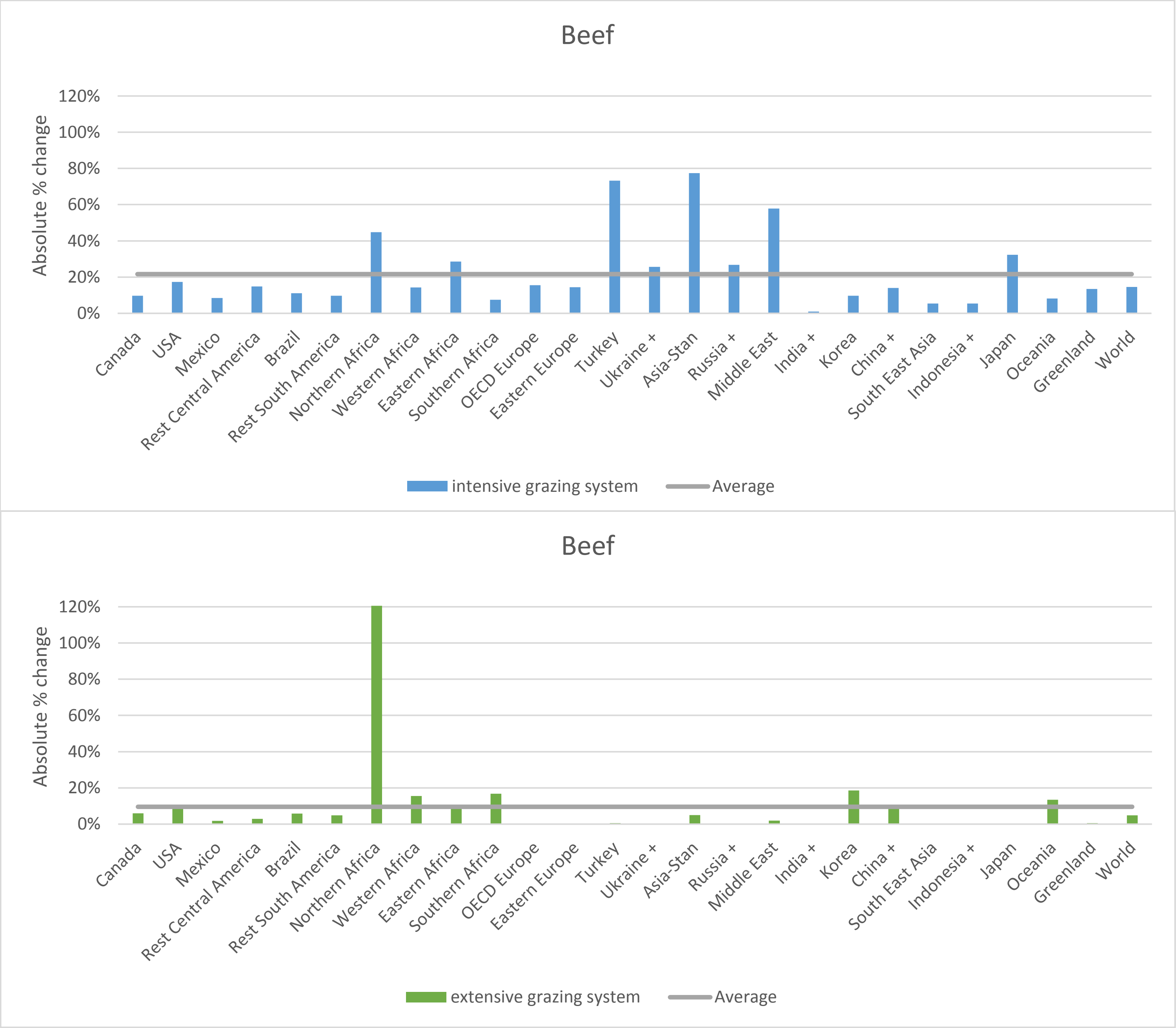

Figure D.1 & D.2. Absolute percentage change in beef emission intensities (intensive and extensive)

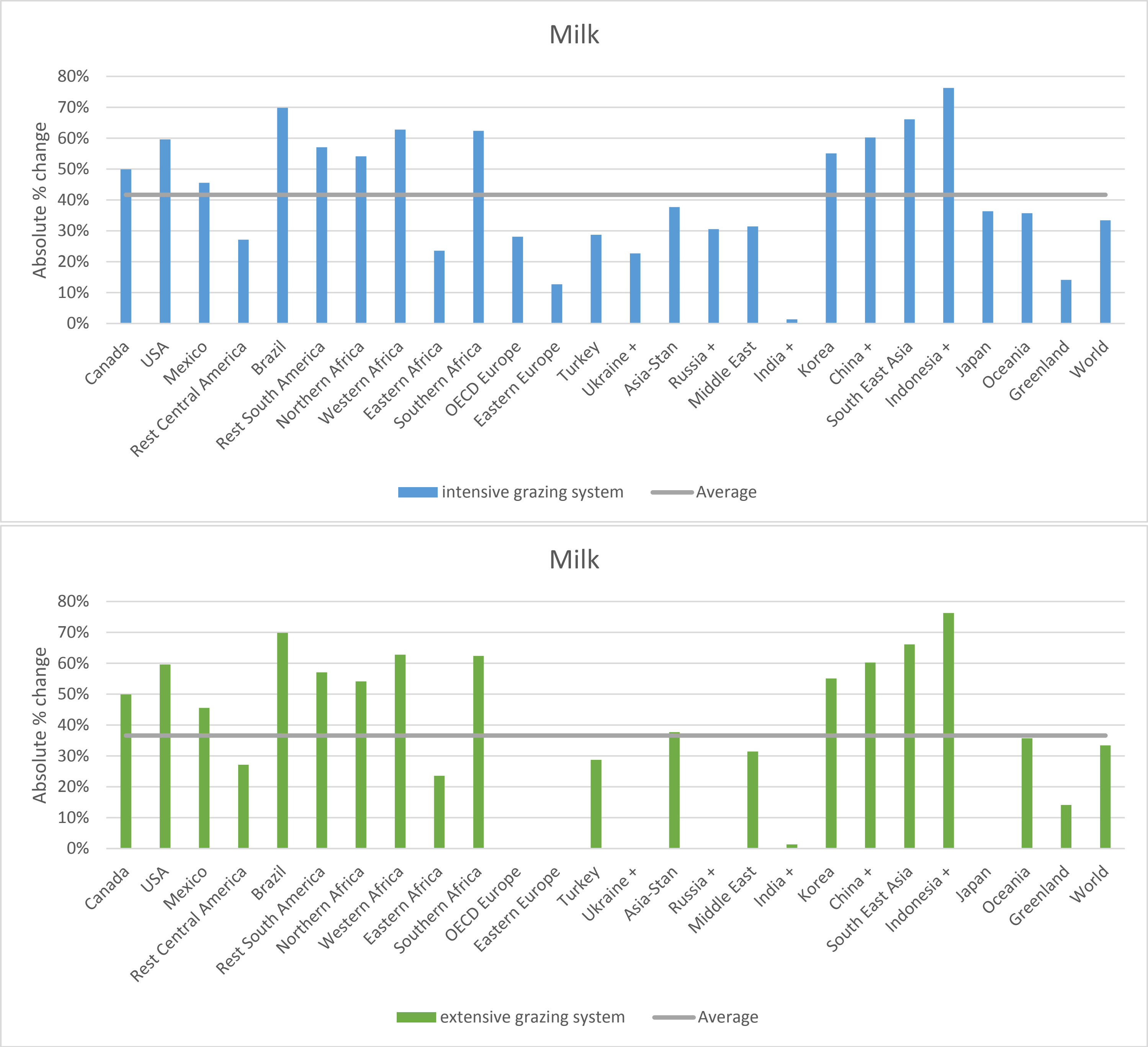

Figure D.3 & D.4. Absolute percentage change in milk emission intensities (intensive and extensive)