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Intensification pathways for beef and dairy cattle production systems: Impacts on GHG emissions, land occupation and land use change

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ABSTRACT

Cattle production is characterized by high land requirements, and greenhouse gas (GHG) emissions associated with the resulting land use change (LUC) and cradle to farm gate processes. Intensification of cattle production systems is considered an important strategy for mitigating anthropogenic GHG emissions. When categorizing production practices into three systems, i.e. pasture-based, mixed and industrial systems, intensification can either take place within one system or through the transition to another more productive system. This study investigates the impacts of these two pathways on farm gate emissions and LUC-related emissions (expressed in kg CO_2-eq per kg of milk or beef) in nine world regions. First, a review is conducted of bottom-up studies on farm gate emissions (without LUC) from dairy production in Europe and beef production in North America and Brazil. Then, a global data set on GHG emissions from cattle production is used to discuss the GHG emission impacts of the two development pathways in other regions. Finally, the GLOBIOM model is applied to perform a global assessment of land occupation and LUC-related emissions. For dairy in Europe, farm gate emission reductions of 1%–14% are found for intensification within one system and 2%–26% for system transitions. In Europe as well as other developed regions, the comparative influence of both pathways on the GHG balance largely depends on the specific design of the initial and final production systems. In developing countries especially, there is a greater potential for emission reductions through intensification within the pasture-based system. The additional reduction potential of moving from pasture-based to mixed and industrial production is limited. Also, emission reductions of intensification within the mixed system are smaller compared to the pasture-based system. For beef production in Brazil, intensification within pasture-based systems can attain significant farm gate emission reductions (>50%). The same is true for pasture-based systems in other developing regions and also some developed regions. Furthermore, the additional GHG reduction potentials of moving from pasture-based to mixed systems, and of intensification within mixed systems are larger for beef than for dairy. Although both the dairy and beef sector can often attain significant farm gate emission reductions through intensification within pasture-based systems, the transition to mixed systems is important to reduce land occupation and LUC-related emissions. LUC mitigation is considered to be the most important GHG mitigation strategy for cattle production in Sub-Saharan Africa and Latin America. Important, but technically and economically constrained strategies to reduce both farm gate and LUC-related emissions include increasing the productivity of grassland and cropland, and increasing the animal productivity through improved feed quality.

1. Introduction

The livestock sector is an important user of natural resources and has significant influence on local landscapes and ecosystems (Herrero et al., 2011; McMichael et al., 2007; Phillips et al., 2006).

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This sector is responsible for approximately 15% of the global greenhouse gas (GHG) emissions and is therefore one of the main contributors to climate change (Bellarby et al., 2013; Gerber et al., 2013). In addition, the land required for livestock production, both direct for grazing and indirect for feed crop cultivation, accounts for 70% of the global agricultural land area and covers up to 30% of the ice-free terrestrial surface of the planet (Steinfeld et al., 2006a). The impact on GHG emissions and land occupation is especially large for cattle production, which accounts for an estimated 65% (Gerber et al., 2013) or even 77% (Herrero et al., 2013) of the total livestock-related GHG emissions. Also, land use change (LUC) related emissions can make up a significant share of the GHG balance of cattle production (Havlík et al., 2014).

While current emissions are large, there is a significant potential to reduce the GHG impacts from dairy and beef production. For example, Gerber et al. (2013) estimate that the livestock sector emissions can be reduced by approximately 30%. About 65% of these reductions can be attained in the cattle sector. To reduce emissions, numerous GHG mitigation options are suggested (e.g. Eckard et al., 2010; Hristov et al., 2013; Smith et al., 2008). Such mitigation strategies are often related to intensification of cattle production. Intensification can be realized by, for example, fertilizing pastures to enhance the pasture productivity, reducing the grazing period and adding more concentrated (less fibrous) feed to the diet (Eckard et al., 2010; Hristov et al., 2013; Smith et al., 2008). As a result of improved feed quality (feed digestibility), the intensity of methane emissions (per kg of beef or milk) from enteric fermentation declines (Herrero et al., 2013). Higher feed quality also increases animal productivity (quantity of milk or beef produced per animal), which leads to a further decline of the non-CO_2 emission intensity. However, the housing of animals, production of feed crops and use of fertilizers may increase the emissions from manure management, feed production and energy use, and partially counteract the direct cattle emission reductions from intensification.

To study global livestock production, production practices are generally categorized into three well-contrasted systems, i.e. pasture-based, mixed and industrial systems (Robinson et al., 2011; Seré et al., 1996). When using this system classification in the context of intensification in the cattle sector, a distinction can be made between (i) intensification within one system and (ii) transitions from one system to a more efficient and productive system (i.e. from pasture-based to mixed and from mixed to industrial). Due to the clear distinction between the systems, these two pathways imply different natures of change. While intensification within one system is characterized by incremental change, a system transition involves transformational change. Therefore, it is expected that these two development pathways will have different impacts on the GHG balance and land occupation. However, this has not been investigated yet in a systematic way. Although a large number of studies has investigated the GHG performance of dairy and beef production systems, and to a lesser extent also the potential of GHG mitigation options (Havlík et al., 2014; Schader et al., 2014), they lack a clear comparison of the effects of the two development pathways. In addition, has not been assessed how the impacts differ between regions. Better insight in these aspects is valuable for designing strategies and policies for future sustainable development of the cattle sector. Therefore, the aim of this study is to compare the GHG emission impacts of intensification within one system and of system transitions. This is done for three indicators: cradle to farm gate GHG emissions, land occupation and LUC-related emissions. The assessment considers both dairy and beef production in nine world regions, based on results from studies in the literature and on data and simulations from the Global Biosphere Management Model (GLOBIOM).

The remainder of this paper is structured as follows: Section 2 describes our approach, the production systems considered, and the impact categories selected to assess the effects of intensification. Section 3 discusses the respective impacts of each development pathway on GHG emissions without LUC, land occupation and LUC-related emissions, and compares the impacts of the two pathways in each region. Section 4 offers a discussion, and conclusions are drawn in Section 5.

2. Materials and methods

2.1. Selection of literature data

For the assessment, literature studies were collected that conduct analyses of the GHG impacts and land requirements of dairy or beef production systems in specific regions, based on bottom-up data. Each study was selected based on the use of similar system boundaries and emission sources, the availability of data on the total milk or beef production, and the ability to convert the results to the functional unit used in the present study (see Section 2.3). In total, 72 studies on dairy production (from 31 publications) and 47 studies on beef production (from 17 publications) were found. The majority of the studies was published in 2009 or later and assessed production systems that represent typical systems in the considered region. Therefore, the studies are considered to provide a good representation of current production practices in the regions covered. The majority of studies are based on modeling exercises instead of actual experiments. Still 22 studies on dairy production (from 11 publications) and 24 studies on beef production (from 7 publications) are based on actual experiments. A detailed overview of all studies, including their main specifications and results, is provided in the Supplementary material (S1–S4).

Table 1 gives an overview of the number of studies per region and shows that the different world regions are not equally covered. Therefore, the dataset from Herrero et al. (2013) is used to discuss the GHG emission impacts of the two development pathways in regions that are poorly covered by the literature. This dataset provides a consistent picture of, for example, feed use, feed conversion efficiency and non-CO_2 GHG emissions for cattle production in 30 regions (see table S7 in the Supplementary

Table 1
Number of studies on GHG emissions from dairy and beef cattle by region and production system. An overview of the studies included in this review and their main characteristics is provided in the Supplementary material (S1 and S2).

Production system	Europe		Asia[a]		Africa[a]		North America		Latin America and the Caribbean[b]		Oceania		Total	
	Dairy	Beef	Dairy	Beef	Dairy	Beef	Dairy	Beef	Dairy	Beef	Dairy	Beef	Dairy	Beef
Pasture-based	17	2						1	2	10	2	4	21	17
Mixed	26	17					4	7	2	0	3	4	35	28
Industrial	6			1			9	1	1				16	2
Total	49	19	0	1	0	0	13	9	5	10	5	8	72	47

[a] When considering nine world regions in this study, Asia is divided into three world regions and Africa is divided into two world regions (Herrero et al., 2013).
[b] In the rest of the article, this region will be referred to as Latin America.

material) in the year 2000. However, the trade-off compared to the studies from the literature is that the data is reconstructed from different global datasets instead of from bottom-up data (Herrero et al., 2013).

The studies in the literature do not always include an analysis of land occupation and LUC-related emissions. Therefore, the impacts of intensification are first discussed based on GHG emissions without LUC. Thereafter, the dataset from Herrero et al. (2013) is used in the Global Biosphere Management Model (GLOBIOM) to perform a systematic assessment of land occupation and LUC-related emissions in nine world regions (Havlík et al., 2014). GLOBIOM is a global partial equilibrium model integrating the agricultural and forestry sectors in a bottom-up setting based on detailed grid cell information. The model is used to analyse the competition for land between agriculture, forestry, and bioenergy, and has been applied in recent key studies about the effect of livestock productivity developments on climate change mitigation (Havlík et al., 2014; Valin et al., 2013b).

2.2. Cattle production systems

All studies from the literature are classified into three production systems: pasture-based, mixed and industrial systems. This is based on the systems classification from Seré et al. (1996) and Robinson et al. (2011), see table S6 in the Supplementary material. The three production systems are defined as following:

1 Pasture-based: production system in which cattle are grazing year-round or for a large part of the year. The diet includes pasture forage (which may also include grains or legumes like wheat or clover), indoor grass feeding, grass silage and hay (Dick et al., 2015; Hörtenhuber et al., 2010; Ruviaro et al., 2014). A small share of the diet can consist of imported, low quality concentrates (Hörtenhuber et al., 2010). Milk production, beef production and stocking rate per hectare are relatively low (Cederberg et al., 2009; Flysjö et al., 2011; Smeets et al., 2007).
2 Mixed: production system in which grazing is still important, but complemented with more concentrated, higher quality feed like soybean meal (Herrero et al., 2009; Robinson et al., 2011). In beef production, calves are first raised on pasture before they are finished on feedlots or in stall barns (Pelletier et al., 2010). Feed crops are imported and/or partially produced on the farm (Herrero et al., 2009; Robinson et al., 2011). Milk production, beef production and stocking rate per hectare are higher than from pasture-based systems.
3 Industrial: production system in which cattle are confined to a stall barn or feedlot. Animals are fed a balanced feed mix including silage, high quality concentrates and a combination of feed supplements, vitamins and medicine (Gerber et al., 2013; O'Brien et al., 2012). Grazing is less important or entirely excluded. In beef production, calves are sent directly to a feedlot (Pelletier et al., 2010). Milk production, beef production and stocking rates per hectare are highest among the three production systems addressed here.

Herrero et al. (2013) and GLOBIOM also use the livestock classification system from Robinson et al. (2011) and include pasture-based and mixed systems but exclude industrial systems, see Table S6 in the Supplementary material. They also include *urban* and *other* production systems, which cannot be categorized as pasture, mixed or industrial. These systems are excluded from the assessment.

2.3. Functional unit and data standardization

In the literature, GHG emissions and land occupation are expressed in various functional units. The present study uses the *fat and protein corrected milk equivalent (FPCM)* for dairy cattle and *carcass weight equivalent (CW)* for beef cattle as functional units. Both are widely used in literature and in key modelling studies (Gerber et al., 2010; Gerber et al., 2013). The FPCM is a standard used to compare milk with different fat and protein contents to evaluate milk production of different dairy cattle on a common basis. FPCM is calculated from the amount of raw milk and the fat and protein content, Eq. (1) (Gerber et al., 2010). If the fat or protein percentage is unknown, milk is converted to FPCM with 4.0% fat and 3.3% protein (Gerber et al., 2013).

$$FPCM(kg) = raw\ milk(kg) * (0.337 + 0.116 * fat\ content(\%) + 0.06 * protein\ content(\%)) \quad (1)$$

The CW can be calculated from the live weight (LW) or bone-free meat (BFM) by using a dressing percentage, Eqs. (2) and (3). The dressing percentage varies per country because the breed, gender, diet, season of slaughter and other factors affect the dressing rate (McKiernan et al., 2007). However, data on dressing percentages is scarce. Therefore, the dressing percentage for all

Table 2
Summary of the main GHG emission sources and the related processes included in the studies from literature, Herrero et al. (2013) and GLOBIOM.

Main source of GHG emissions	Characteristics	Produced greenhouse gas	Studies from literature	Herrero et al. (2013)	GLOBIOM
Enteric fermentation	Enteric fermentation	CH_4	X	X	
Manure management	Manure storage, processing and deposit	Direct and indirect N_2O and CH_4	X	X	
Feed production	Manure applied to feed crops and pasture or directly deposited on pastures by animals	Direct N_2O	X	X	
	Synthetic fertilizer applied to feed crops and pastures from decomposition of crop residues	Direct and indirect N_2O	X	X	
	Volatilisation and leaching	Indirect N_2O	X	X	
	Production, processing and transport of feed and fertilizer	CO_2	X	–	
Energy consumption	On-farm energy use	CO_2	X	–	
Land use	SOC change during cultivation	CO_2	X[b]		X[c]
LUC	Pasture expansion or decline	CO_2	X[c]		–
	Cropland expansion or decline	CO_2	X[c]		–
	Conversion from forest land to pasture or cropland (deforestation)	CO_2	–		X
	Conversion from natural land[a] to pasture or cropland	CO_2	–		X

[a] Natural land is all land other than forest, cropland, land being grazed by livestock or other agricultural land, wetlands, bareland and urban areas (Mosnier et al., 2013).
[b] Only included in some studies from the literature.
[c] Only accounted for in Europe (Frank et al., 2015).

countries and regions has been assumed to be 60% for LW and 150% for BFM (Opio et al., 2013).

$$CW(kg) = LW(kg) * dressing\ percentage(\%) \tag{2}$$

$$CW(kg) = BFM(kg) * dressing\ percentage(\%) \tag{3}$$

2.4. Cradle to farm gate GHG emissions

The present study investigates the cradle to farm gate GHG emissions per kg of milk or beef produced. This includes emissions from all upstream processes in cattle production up to the point where the animals or products leave the farm. The main emission sources are enteric fermentation, manure management and feed production (Herrero et al., 2013), see Table 2. The studies from the literature also take into account indirect emissions from the production of farm inputs, emissions from energy consumption, and sometimes emissions from land use (Table 2). GHG emissions from the production and use of pesticides, medicines or detergents are excluded in the present study, as their share in the total GHG balance is very small and most studies do not cover these sources (Gerber et al., 2013). Also, LUC-related emissions are left out from the cradle to farm gate emissions, but assessed separately (see Section 2.6). A majority of the studies calculates the GHG emissions based on life-cycle assessment (LCA). Thirteen publications use another approach or model to assess the GHG emissions (e.g. Lovett et al., 2008; O'Brien et al., 2012), see the Supplementary material (S1 and S2). In Herrero et al. (2013), cattle non-CO_2 emissions are calculated using a digestion and metabolism model for ruminants.

The results from the literature for different regions and from different references are difficult to compare because of the influence of local conditions like climate and the differences in assumptions made with regard to, for example, the functional unit, allocation methods and characterization of the production processes (Dick et al., 2015; Ruviaro et al., 2014). Therefore, the GHG emission impacts of intensification within one system and of system transitions are first discussed based on studies from the same reference and for the same region or country. This comparison concentrates on selected larger regions for which all production systems are covered by the literature. For dairy, Europe is considered and for beef the analysis includes the USA, Canada and Brazil. Subsequently, the data from Herrero et al. (2013) is used to discuss what the GHG emission impacts of the two development pathways may be in other regions.

2.5. Land occupation

Land occupation is defined as the area of land needed to produce one kg of milk or beef. This includes grassland and cropland, as well as on-farm land use and land required to produce imported feed. When land occupation is not directly available from a study, but sufficient data is available about total land use and total beef or milk production, land occupation (LO) is derived by applying Eq. (4).

$$LO(m^2/kgFPCM\ or\ CW) = \frac{total\ grassland\ \ or\ cropland\ requirement\ (ha) * 10000(m^2/ha)}{total\ milk\ or\ beef\ production\ (kgFCPM\ or\ CW)} \tag{4}$$

Comparable to the GHG emissions, the impact of the two development pathways on land occupation is first discussed for Europe and North America based on results from the studies in literature. Then, the results from GLOBIOM are used to discuss how the development pathways may influence land occupation in other regions.

2.6. LUC-related emissions

LUC-related emissions are defined as GHG emissions caused by a change from one land use to another, e.g. the change from forests

Table 3
Key factors identified as reasons for differences in emissions between dairy production systems.

Production system (s) compared	Production system types compared	Main reasons for differences in emissions	Main emission sources influenced
Pasture-based	Conventional	Grass productivity (Hörtenhuber et al., 2010), cattle stocking density (Hörtenhuber et al., 2010; O'Brien et al., 2010), cow genotype (O'Brien et al., 2010)	Feed production
	Organic vs. conventional	Synthetic fertilizer use, SOC sequestration in organic and SOC losses in conventional (Hörtenhuber et al., 2010)	Feed production
Mixed	Conventional	Energy and fertilizer use (Haas et al., 2001), animal productivity[a] (Bell et al., 2011; Hörtenhuber et al., 2010), cow genotype, genetic selection for increased milk production and fertility (O'Brien et al., 2010), genetic selection of cows for increased milk fat and protein production (Bell et al., 2011)	Enteric fermentation, feed production
	Similar systems (organic or conventional)	Feed conversion efficiency, land use intensity, share of imported feed (Kristensen et al., 2011)	Enteric fermentation, feed production
	Organic vs. conventional	Feed quality (Hörtenhuber et al., 2010; Olesen et al., 2006), synthetic fertilizer use (Hörtenhuber et al., 2010), cattle stocking density, grazing period, animal productivity[a] (Kristensen et al., 2011)	Enteric fermentation, feed production
Industrial	Conventional	Genetic selection of cows for increased milk fat and protein production, animal productivity[a] (Bell et al., 2011)	All
Pasture-based vs. mixed	Conventional	Climatic conditions (Schader et al., 2014), pasture productivity (Lovett et al., 2008), feed quality (O'Brien et al., 2010), animal productivity[a] (Hörtenhuber et al., 2010; Lovett et al., 2008; O'Brien et al., 2010; Schader et al., 2014)	Enteric fermentation, feed production
	Organic pasture-based vs. conventional mixed	Cattle stocking density (Thomassen et al., 2008), feed quality (Williams et al., 2006), animal productivity[a], fossil energy and fertilizer consumption (Haas et al., 2001)	Enteric fermentation, manure management
Pasture-based or mixed vs. industrial	Conventional	Manure management, energy consumption (O'Brien et al., 2012), feed quality (Williams et al., 2006), animal productivity[a] (Bell et al., 2011)	All

[a] Animal productivity here refers to milk production per animal.

to cropland in order to allow the expansion of crop production. As the number of studies that assess LUC-related emissions is small (Bartl et al., 2011; Belflower et al., 2012; Bonesmo et al., 2013; Hörtenhuber et al., 2010; Nguyen et al., 2012), only results for dairy production in Europe are discussed. The results from GLOBIOM are used as the main input for the discussion on the share and size of LUC-related emissions in the GHG balance of cattle production in each region (Havlík et al., 2014). In GLOBIOM, land use change results from choosing land use and processing activities with the aim to maximize social welfare (while subject to resource, technological, and policy constraints) (Havlík et al., 2011). The relevant land use change processes in GLOBIOM are the conversion of forest or natural land to pasture or cropland (Table 2). CO_2 emissions or sequestration are calculated as the difference in carbon content in above- and below-ground living biomass between the initial and new land use (Mosnier et al., 2013).

3. Results

3.1. Impact of intensification on cradle to farm gate GHG emissions

3.1.1. Intensification within one system

When considering the cradle to farm gate GHG emission balance, the review of studies on *dairy production* in Europe shows that intensification within both the pasture-based and mixed production system often results in decreasing GHG emissions. For example, in pasture-based systems, Hörtenhuber et al. (2010) find that emissions are about 0.07 kg CO_2-eq/kg FPCM or 6%–7% lower in upland pasture systems compared to alpine pasture systems that have lower grass productivity and cattle stocking density. Also, O'Brien et al. (2010) find that a higher stocking rate reduces emissions by 0.01–0.03 kg CO_2-eq/kg FPCM (1–3%). Regarding mixed systems, Hörtenhuber et al. (2010) and Bell et al. (2011) find that the emissions are 0.10–0.13 kg CO_2-eq/kg FPCM or 8–14% lower in systems that attain higher milk yields. However, not all studies find the same trend and this depends on the precise strategy used for intensification. For example, according to O'Brien et al. (2010), emissions in both pasture-based and mixed systems are 0.05–0.14 kg CO_2-eq/kg FPCM (5–16%) higher for cows solely selected for high milk production compared to cows selected for both increased productivity and fertility. The difference is largest for pasture-based systems (O'Brien et al., 2010). Also, Haas et al. (2001) find that the emissions of an intensive mixed system are 0.30 kg CO_2-eq/kg FPCM (30%) higher compared to an extensive mixed system. In the intensive mixed system, benefits from improved animal productivity are reduced by increased fossil energy and fertilizer consumption (Haas et al., 2001). When comparing conventional and organic production, Hörtenhuber et al. (2010) find for both pasture-based and mixed systems that emissions from organic dairy production are up to 0.08 kg CO_2-eq/kg FPCM lower compared to conventional production because of, for example, not using synthetic fertilizers in organic production (see Table 3). The difference between conventional and organic production is largest for pasture-based systems (Hörtenhuber et al., 2010). But also here, results differ across studies. Kristensen et al. (2011) and Olesen et al. (2006) find for mixed dairy systems that the emissions from organic production are respectively 0.07 and 0.14 kg CO_2-eq/kg FPCM higher than conventional production. This is mainly because of higher feed quality and higher animal productivity in conventional production than in organic production.

For industrial dairy production, fewer studies are available. Bell et al. (2011) find that an improved system with cows selected for increased milk fat and protein production attains a higher milk yield per cow and slightly reduces emissions per kg of milk compared to a system with average milk fat and protein production. The difference in emissions between the two industrial systems is 0.09 kg CO_2-eq/kg FPCM (8%), which is a bit smaller than for mixed systems (Bell et al., 2011).

Intensification in pasture-based *beef production* systems in Brazil has a significant potential for reducing GHG emissions. For example, Dick et al. (2015) compare an extensive grazing system to an enhanced system characterized by improved pasture, the introduction of other forage species and rotational grazing. They find that the emissions of the improved system are less than half of the extensive system (15.4 vs. 36.0 kg CO_2-eq/kg CW). Ruviaro et al. (2014) compare various pasture-based systems with different grasses and crops (natural and improved natural grass, ryegrass, sorghum) and management levels. The variation in emissions between the systems is large (ranging from 32.0 to 68.2 kg CO_2-eq/kg CW). Overall, the lowest emissions are attained in systems with the shortest animal lifetime and highest cattle density. In most cases, these are also the systems with the highest feed quality (improved pastures). One exception is the system based on natural grass and a protein-energy mineralized salt supplement. This system has a lower feed quality and cattle density compared to the system based on natural grass and ryegrass, but the salt supplement improves the feed conversion rate, shortens the lifetime of the animals and thereby reduces the total emissions (37.4 kg CO_2-eq/kg CW) compared to the natural grass and ryegrass-based system (47.4 kg CO_2-eq/kg CW) (Ruviaro et al., 2014).

For intensification of mixed beef systems in Canada, GHG reduction potentials are lower. Basarab et al. (2012) investigate four systems which differ in animal lifetime (age at which animals are started on their finishing diet) and use of hormone implants. For animals implanted with hormones, the total emissions are 1.2-1.3 kg CO_2-eq/kg CW or 6% lower compared to systems not implanted with hormones. Basarab et al. (2012) also find that emissions are 1.3–1.4 kg CO_2-eq/kg CW (7%) higher for systems with longer animal lifetimes. For beef, no studies were found that compared different industrial production systems.

3.1.2. System transitions

When comparing pasture-based and mixed *dairy production* systems in Europe, Hörtenhuber et al. (2010), Thomassen et al. (2008), Haas et al. (2001), Williams et al. (2006), O'Brien et al. (2010) and Schader et al. (2014) find that emissions for mixed systems are generally lower compared to pasture-based systems (reductions of 0.02–0.30 kg CO_2-eq/kg FPCM, or approximately 2%–26%). Key reasons for emission reductions are increased feed quality, animal stocking density and animal productivity, see Table 3. In Haas et al. (2001), Thomassen et al. (2008) and Williams et al. (2006), the pasture-based system is an organic system, while the mixed system is based on conventional production. Yet, when the emissions from an organic pasture-based system are lower compared to a conventional pasture-based system, as found by Hörtenhuber et al. (2010), the emissions of conventional mixed dairy production will also be lower compared to conventional pasture-based production. In Lovett et al. (2008), the emissions from the mixed system are 0.09 kg CO_2-eq/kg FPCM (10%) higher compared to pasture-based production. In this study, the pasture-based system attains a higher pasture productivity compared to the mixed system. The additional concentrates in the mixed system do not compensate for this. As a result, animal productivity is also higher in the pasture-based system (Lovett et al., 2008).

A transition from pasture-based or mixed to industrial dairy production in Europe may decrease or increase the GHG balance depending on, for example, the increase in feed quality and in emissions related to manure management (Bell et al., 2011; O'Brien et al., 2012; Williams et al., 2006), see Table 3. Williams et al. (2006) find that emissions in an industrial system are reduced by

0.25 kg CO_2-eq/kg FPCM (20%) compared to pasture-based production and by 0.08 kg CO_2-eq/kg FPCM (8%) compared to mixed production. Bell et al. (2011) also find a reduction in emissions compared to mixed dairy production (difference of 0.16–0.18 kg CO_2-eq/kg FPCM or 14%). In contrast, O'Brien et al. (2012) find an increase of 0.05 kg CO_2-eq/kg FPCM (6%) when moving from a pasture-based to an industrial system.

For *beef production* systems in the USA, Pelletier et al. (2010) compared pasture-based, mixed and industrial systems. A transition from pasture-based to mixed (backgrounding and feedlot finishing) and from mixed to industrial (finishing on feedlots only) production both result in decreased emissions (for key factors behind these differences see Table 4). Similar to the results for dairy production, the benefit is larger for the step from a pasture-based to a mixed system (from 30.7 to 25.9 kg CO_2-eq/kg CW or 16% reduction) than from a mixed to an industrial system (from 25.9 to 23.7 kg CO_2-eq/kg CW, 9% reduction) (Pelletier et al., 2010).

3.1.3. Comparing results for intensification within one system and system transitions

Most studies on *dairy production* in Europe show that both intensification within one system and through system transitions result in decreased GHG emissions per kg of milk produced. Reduction potentials found for intensification within one system are 1%–7% for pasture-based systems, 8–14% for mixed systems and about 8% for industrial systems. GHG mitigation potentials of system transitions are 2%–26% from pasture-based to mixed production and 8%-14% from mixed to industrial systems. However, these figures are based on a limited number of studies and should only be considered as an indication of attainable reduction potentials. In addition, for both development pathways a few exceptions are found for which intensification did not result in GHG emission reductions. First, organic or extensive dairy production sometimes reduces emissions compared to more intensive conventional production because of not using any synthetic fertilizers, lower fossil fuel consumption and the occurrence of soil organic carbon sequestration (Haas et al., 2001; Hörtenhuber et al., 2010). Second, moving to an industrial production system may either decrease emissions because of increased feed quality and animal productivity or increase emissions because of higher emissions from manure management and energy consumption (Bell et al., 2011; O'Brien et al., 2012; Williams et al., 2006).

A comparison of the results from literature studies and the data from Herrero et al. (2013) (Fig. 1A) shows that the emission values of all production systems in Europe are relatively close to one another compared to other regions. Therefore, whether the influence on the GHG balance is larger for intensification within one system or for a system transition will depend on the specific design of the initial and final production systems. When considering more regions (Fig. 1A), the same seems to apply for other developed regions, i.e. North America and Oceania. In developing regions, however, the differences within and between pasture-based and mixed systems are more significant than in developed regions. Also, average non-CO_2 emissions in these regions, especially from pasture-based production, are higher compared to developed regions. Although practices in developed countries cannot be adopted one to one in developing countries, these differences suggest that there is a great potential to mitigate GHG emissions in developing regions through intensification within pasture-based systems. This potential may often be as high as the emission reduction that can be attained by a transition from pasture-based to mixed production. Probably, the most important limitation for emission reductions in the pasture-based system is the climate. As shown in GLOBIOM results, emissions are generally significantly higher in arid areas than in humid and temperate regions. Nevertheless, the GLOBIOM results show that pasture-based dairy production in arid regions in South Africa attains higher milk yields and lower emissions compared to other Sub-Saharan arid regions. Management practices in South Africa may therefore provide good options for improvements in the other regions. Thus, for all developing regions it is interesting to compare current management practices with best practices available in their own region and in other regions and to investigate options to improve the production system. With regard to mixed systems, the differences in emissions between regions are smaller than for pasture-based systems. However, in some regions and especially Sub-Saharan Africa, there may still be significant potentials to reduce emissions through intensification within the mixed system. In addition, the studies from literature indicate that a smaller additional emission reduction may be attained by a transition to the industrial system. In this case it is important to adopt measures that minimize GHG emissions from manure management and energy consumption.

Based on the studies on *beef production*, GHG emission reductions in pasture-based systems in Brazil could exceed 50% when changing from extensive, natural grass-based pastures to improved pastures. However, when the initial and/or final design of the production system are in between these two ends, the mitigation potential will be lower. Intensification of mixed systems in Canada is found to result in an emission reduction of 6%–7%. For a transition from pasture-based to mixed production in the USA, emissions are found to be reduced by 16%. Transitioning from a mixed to industrial system results in a decrease of 9% in GHG emissions. When considering the GLOBIOM results for all regions, several observations are made. First, for both pasture-based and mixed beef systems the variation in non-CO_2 emissions between the developed regions (Europe, Oceania and North America) is larger compared to dairy systems (Fig. 1B). Second, also the difference in average emissions between pasture-based and mixed beef systems in Europe is more significant than for dairy. Third, with regard to mixed systems, the emissions of beef production vary more between all regions compared to milk production. An important explanation for these observations is considered to be the larger variation in production systems, for example with regard to pasture types and animal slaughter age. These are aspects that

Table 4
Key factors identified as reasons for differences in emission between beef production systems.

Production system(s) compared	Production system types compared	Main reasons for differences in emissions	Main emission sources influenced
pasture	Conventional	Pasture productivity, feed quality, weight gain, animal productivity[a] (Dick et al., 2015), lifetime, cattle density (Ruviaro et al., 2014)	Enteric fermentation, manure management, feed production
mixed	Conventional	Hormone implants, carcass weight, lifetime (Basarab et al., 2012)	Enteric fermentation, manure management, feed production, energy use
Pasture vs. mixed and mixed vs. industrial	Conventional	Feed quality, animal growth rate, lifetime (Pelletier et al., 2010)	Enteric fermentation, manure management, feed production

[a] Animal productivity: beef production per animal.

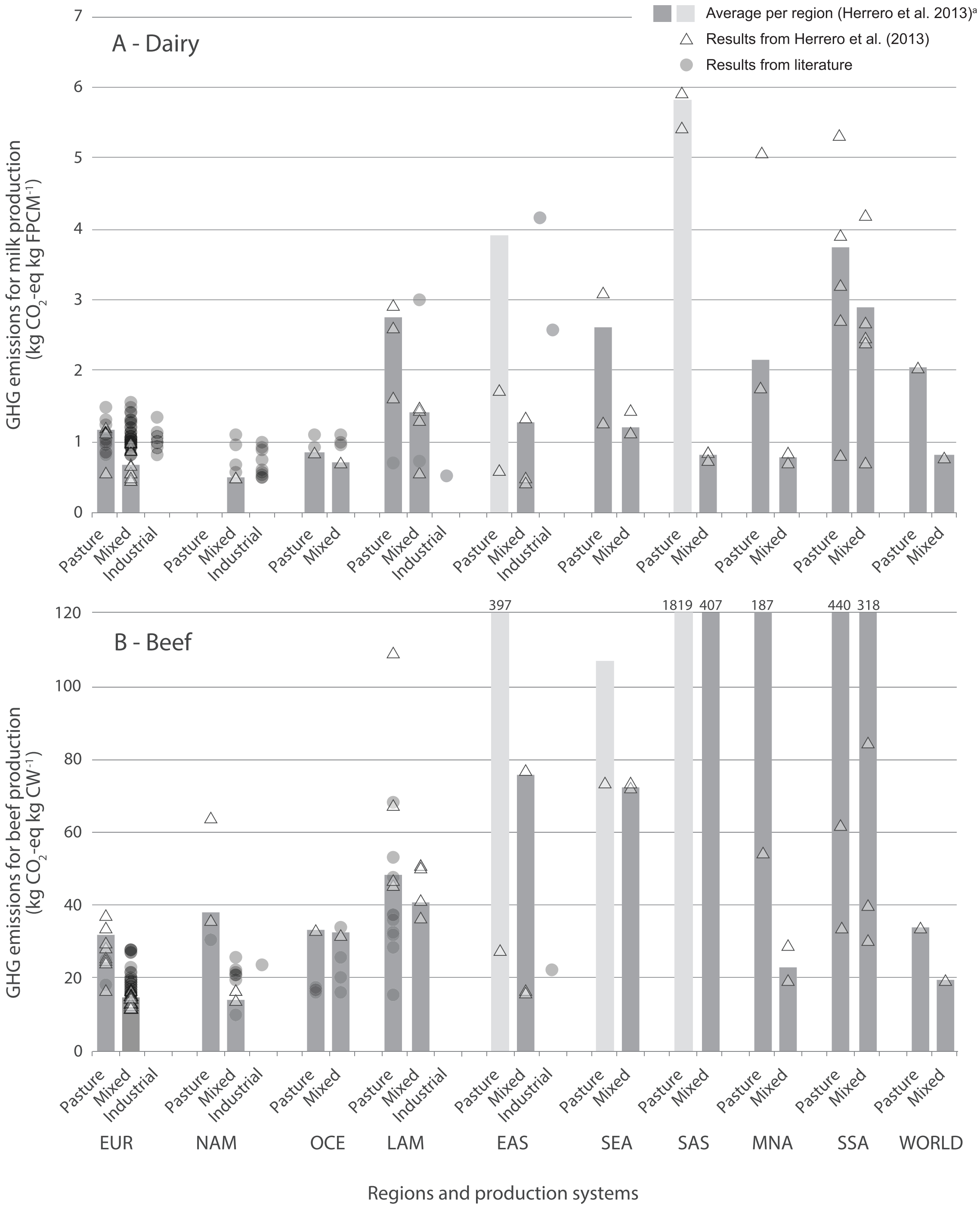

Fig. 1. GHG emissions without LUC emissions for dairy (A) and beef (B) systems per region and production system. The triangles represent the results per sub-region from Herrero et al. (2013) and the dots represent the results from the studies in literature. Average per region is the weighted average of all sub-regions from Herrero et al. (2013). EUR, Europe; NAM, North America; OCE, Oceania; LAM, Latin America and the Caribbean; EAS, East Asia; SEA, South-East Asia; SAS, South Asia; MNA, Middle-East and Northern Africa; SSA, Sub-Saharan Africa.

[a] In panel A, the bars for the weighted average emissions of pasture-based dairy production in East Asia and South Asia are given a different color than the other regions. This is because the number of livestock units in these pasture-based systems are very small compared to the total number of LU in these regions. Similarly, in panel B, the bars for the weighted average emissions of pasture-based beef production in East Asia, South East Asia and South Asia are given a different color than the other regions, because the number of livestock units in these pasture-based systems are very small compared the total number of LU in these regions.

Note 1: In Herrero et al. (2013), there are no results for dairy pasture-based systems in North America and EU regions because pure grass-based milk production is insignificant in these regions and all dairy cattle production systems are classified as mixed. The results presented for pasture-based dairy production in Europe are for the following regions: former USSR, rest of Central Eastern Europe and rest of Western Europe.

Note 2: In panel A and B, the emissions of all systems in the Pacific Islands are very high compared to the average emissions in Oceania, while the number of livestock units (LU) in this sub-region is very low compared to the total LU in Oceania (Herrero et al., 2013). Therefore, the individual results for the Pacific Islands are not included in the figure.

Note 3: In panel B, the results from Herrero et al. (Herrero et al., 2013) for the following production systems and regions are outside the range of the y-axis: pasture-based systems in South Asia (incl. India), Turkey, Eastern, Western and Southern Africa and parts of South East Asia, and mixed systems in South Asia (incl. India), Eastern and Southern Africa.

have a significant impact on the feed quality, feed conversion efficiency and beef yield, and thus on the resulting GHG emissions. This implies that intensification within pasture-based production systems (through adoption of best practises available) cannot only attain considerable GHG reductions in developing regions but also in some developed regions, especially Canada. In addition, GHG mitigation potentials from intensification within mixed beef systems, e.g. in Oceania, parts of Asia and Sub-Saharan Africa, may be larger compared to dairy production. Fourth, the additional GHG reduction potential of moving from pasture-based to mixed systems compared to intensification within pasture-based systems is larger for beef production than for dairy.

The finding that the potential emission reductions from intensification within the pasture-based system can often be as significant as from transitioning to a mixed system confirms results from Gerber et al. (2013). They state that global GHG emissions from beef and dairy production can be reduced by 17%–32% when farmers apply the best practices available for their production system in the same region and climate zone. Also, as significant emission reductions can be attained within pasture-based systems, Gerber et al. (2013) find that only an additional 3% to 5% emission reduction can be attained when farmers are allowed to make the transition from pasture-based to mixed production systems. In line with the findings from the present paper, the additional reductions are highest for beef production (Gerber et al., 2013).

3.2. Impact of intensification on land use change and associated emissions

Despite the more limited additional GHG benefits from a system transition compared to intensification within a pasture-based system, such a transition may still be required for other reasons, such as land scarcity, land use change and associated emissions (Havlík et al., 2014), specifically if LUC occurs in e.g. forest frontier areas. A system transition is important because mixed and industrial systems are generally characterized by lower land occupation than pasture-based systems (see Table 5). For example, for *beef production* in the USA, Pelletier et al. (2010) find that land occupation is 114.7 $m^2\,kg_{CW}^{-1}$ for pasture-based, 91.2 $m^2\,kg_{CW}^{-1}$ for mixed and 74.5 $m^2\,kg_{CW}^{-1}$ for industrial production. According to Williams et al. (2006), the land requirement for beef in the UK is 38.5–42.1 $m^2\,kg_{CW}^{-1}$ in pasture-based systems compared to 22.8–24.1 $m^2\,kg_{CW}^{-1}$ in mixed production. For *dairy production* in Europe, Hörtenhuber et al. (2010) find that land occupation is 1.5–2.4 $m^2\,kg_{FPCM}^{-1}$ for pasture-based and 1.2–1.7 kg_{FPCM}^{-1} for mixed production. In addition, based on Bell et al. (2011), land occupation is 1.1–1.2 $m^2\,kg_{FPCM}^{-1}$ for mixed and 0.6–0.7 $m^2\,kg_{FPCM}^{-1}$ for industrial production. However, according to Williams et al. (2006) and O'Brien et al. (2012), the land requirement in an industrial system is respectively equal to mixed production or 0.2 $m^2\,kg_{FPCM}^{-1}$ higher compared to a pasture-based system due to a higher annual feed intake per cow in the industrial system.

In the previous sections, it was found that organic or extensive dairy production can reduce emissions compared to more intensive conventional production. However, land occupation in an organic or extensive system is higher compared to conventional or more intensive production (Hörtenhuber et al., 2010; Kristensen et al., 2011), which may then be associated with increased LUC emissions depending on the local circumstances. Thus, from a land use perspective, conventional production and intensification may be preferred compared to organic or extensive production. However, the studies by Hörtenhuber et al. (2010) and Haas et al. (2001) highlight the importance to use fertilizers and energy as efficiently as possible, as is demonstrated in other studies as well (Gerber et al., 2013; Lovett et al., 2008; Olesen et al., 2006). This is especially true for mixed and industrial systems, for which the share of emissions from feed production and energy use increase compared to pasture-based systems.

When translating land occupation to land use change emissions, studies from the literature estimate that the effect of the conversion of natural lands and forests to agricultural land was limited to a maximum of 11% of the total emissions from dairy production in Europe (Hörtenhuber et al., 2010; O'Brien et al., 2014, 2012). Also, the share of LUC-related emissions was found to be larger for mixed and industrial systems compared to pasture-based production; this is because of increased feed imports from South America (Hörtenhuber et al., 2010; O'Brien et al., 2012). However, when the GHG balance without LUC-related emissions was lower

Table 5
Land occupation for dairy and beef production per region in grassland and cropland, as calculated in GLOBIOM.

		Dairy			Beef		
		Grassland (m^2/kg FPCM)	Cropland (m^2/kg FPCM)	Total Land (m^2/kg FPCM)	Grassland (m^2/kg CW)	Cropland (m^2/kg CW)	Total Land (m^2/kg CW)
EUR	PB[a]	21.8	–	22	78	1.3	79
	MI	3.5	0.4	4	27	2.2	29
OCE	PB	36.3	–	36	623	–	623
	MI	4.7	0.1	5	115	–	115
NAM	PB[a]	–	–	–	222	3.4	226
	MI	2.5	0.6	3	25	3.6	29
LAM	PB	46.5	0.1	47	416	–	416
	MI	10.1	0.2	10	156	0.1	156
EAS	PB	8.1	0.2	8	429	2.1	431
	MI	0.7	0.4	1	47	4.9	52
SEA	PB	45.4	–	45	733	–	733
	MI	2.2	0.4	2.5	51	–	51
SAS	PB	64.7	–	65	11,909	–	11,909
	MI	1.8	0.6	2	377	–	377
MNA	PB	78.3	–	78	1627	1.4	1629
	MI	3.0	1.0	4	153	6.5	160
SSA	PB	166.8	–	167	16,897	–	16,897
	MI	68.7	0.2	69	9249	0.4	9249
WORLD	PB	49.2	–	49	639	0.7	639
	MI	3.8	0.4	4	199	1.5	201

The regions are defined as in Fig. 1. Production systems: PB, pasture-based; MI, mixed.

[a] There are no GLOBIOM results for dairy pasture-based systems in North America and EU regions, see note 1 for Fig. 1.

for mixed systems compared to pasture-based production, Hörtenhuber et al. (2010) show that this remains true for the GHG balance including LUC. In accordance with the studies from literature, the GLOBIOM results show that the share of LUC-related emissions is small for dairy and beef production in Europe and North America and for beef production in Oceania (Fig. 2). However, LUC-related emissions in both dairy and beef production account for 20% to more than 50% of the total emissions in Latin America, South East Asia and Sub-Saharan Africa. Also, in developing regions, the amount and share of emissions related to LUC are generally higher for pasture-based systems compared to mixed systems (see also S5 in the Supplementary material). In these regions, high numbers of livestock units graze in low productive areas. The low animal productivity and high land occupation then cause significant natural land conversion, degradation and/or deforestation.

Because of the large contribution of LUC, its mitigation is a key strategy for reducing GHG emissions from dairy production in Latin America and from dairy and beef production in Sub-Saharan Africa and parts of Asia. For example, Cohn et al. (2014) show that policy-driven intensification within pasture-based cattle production systems in Brazil could reduce the pasture area by 16–21 million hectares (Mha). As a result, 15–17 Mha of forest could spared from deforestation and emissions associated with deforestation could drop by 75%–80% (Cohn et al., 2014). In Latin America, the share of LUC-related emissions in the total GHG balance is lower for beef (up to 20%) than for dairy (up to 40%). Therefore, the relative GHG potential of LUC mitigation is also lower for beef. However, as the number of livestock units and the total emissions in the beef sector are significantly higher than in the dairy sector, the absolute GHG reduction potential is likely larger for the beef sector.

Several strategies can be identified to reduce LUC-related emissions. First, when new farms are established, these should be based on mixed production systems instead of pastures-based systems. In addition, as illustrated by the study of Cohn et al. (2014), land use change can be mitigated through a reduction in the land occupation of existing cattle production. This can either be attained by moving from a pasture-based to mixed production system, or by reducing the land occupation in the current system. The literature provides several options to realize reduced land occupation: improving the productivity of grassland and cropland, increasing the animal productivity through improved feed quality, and introducing or increasing the amount of crops in the feed

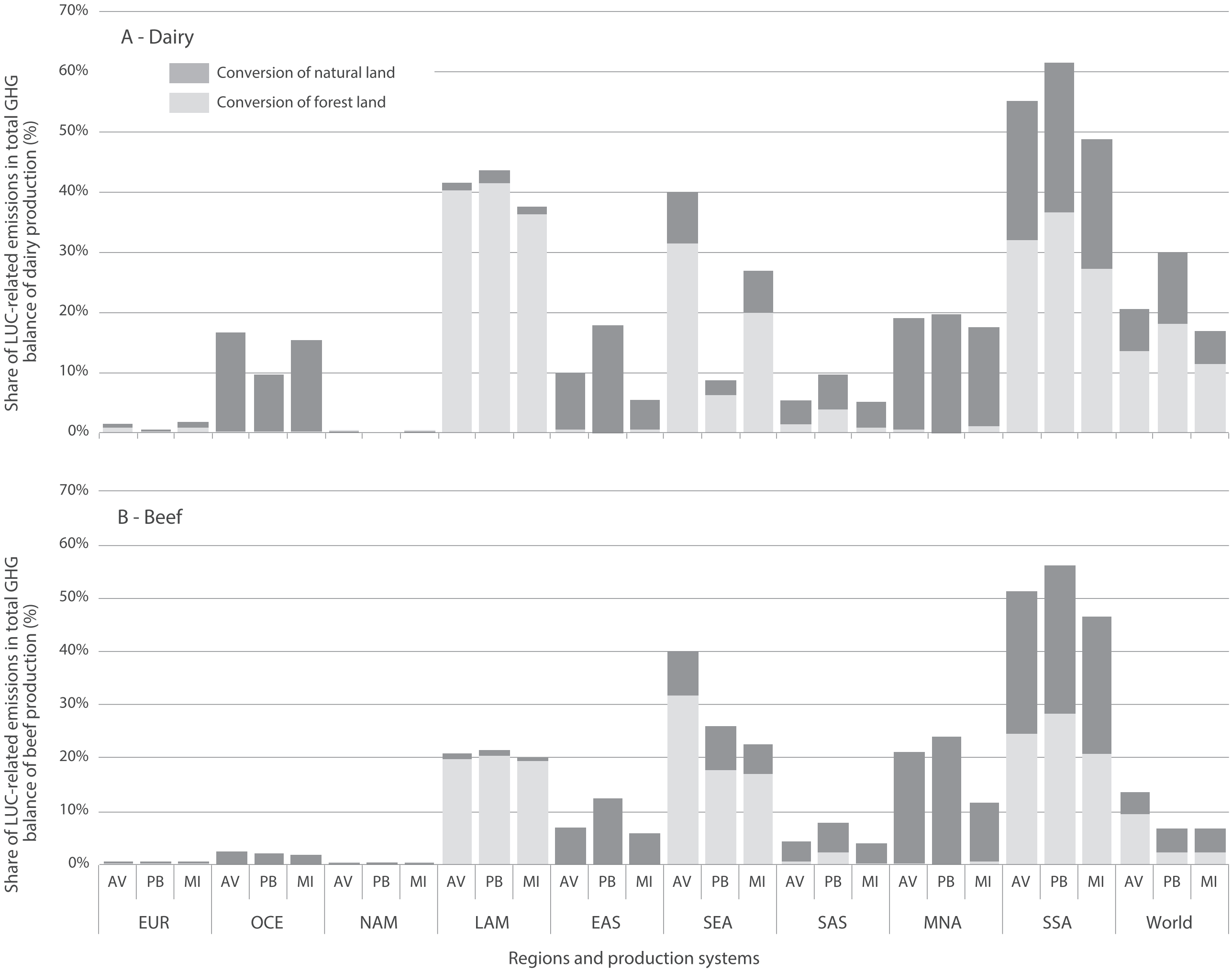

Fig. 2. LUC emissions (related to natural land conversion and deforestation) in terms of percentage of the total GHG emissions for dairy production (A) and for beef production (B). Estimates are obtained from GLOBIOM simulations in Havlik et al. (2014). Regions are defined as in Fig. 1. Production systems: AV, weighted average of all production systems (also including urban and other); PB, pasture-based; MI, mixed. For absolute values of LUC-related emissions, see the Supplementary material (S3 to S5).
Note 1: there are no GLOBIOM results for dairy pasture-based systems in North America, see note 1 for Fig. 1.
Note 2: in South-East Asia, the weighted average LUC-related emissions of all production systems are higher than the emissions from both pasture-based and mixed systems, because the system categories *other* and *urban* are also included in this average.

ration (Bell et al., 2011; Cohn et al., 2014; Dick et al., 2015; Hörtenhuber et al., 2010; Ridoutt et al., 2014). As these options are also identified as strategies to mitigate emissions in general, the total GHG reduction potential of these measures is even larger. In addition, the studies illustrate the importance of good soil management to reduce soil organic carbon losses or even stimulate soil carbon accumulation. For example, Belflower et al. (2012) account for changes in soil organic carbon due to the conversion of cropland to perennial grassland in mixed dairy production in the USA. The resulting SOC sequestration reduces total emissions by 0.07 kg CO_2-eq $kg_{FPCM}{}^{-1}$ or 15%. Also, in the study by Basarab et al. (2012) on mixed beef production in Canada, land has been under rotation between grassland and cropland (cereals and oilseed crops). This rotation results in a net SOC sequestration and an emission reduction of 2.2–3.6 kg CO_2-eq $kg_{CW}{}^{-1}$ (11–16%) (Basarab et al., 2012).

4. Discussion

4.1. Data cover and data quality

The majority of the studies in literature evaluate pasture-based and mixed systems. Few studies have assessed industrial systems, especially in the case of beef production. As a result, the environmental performance of industrial systems in terms of GHG emissions and land occupation cannot be investigated well. The same is true for the GHG reduction potential of the transition from mixed to industrial systems. The influence on LUC and LUC-related emissionsis even largely unknown yet. It is likely that the assessment of industrial systems is lacking because mixed and pasture-based systems are currently dominant in milk and beef production. But to improve the insights in GHG emissions and mitigation potentials for different systems, it is important to pay more attention to industrial systems in bottom-up studies and to include these systems as a separate category in models. This would help to better understand the options for cattle production and GHG mitigation and to develop strategies for improving future beef and milk production. An approach to assess industrial systems when data is limited or lacking could be to use a conceptual design of industrial production systems, i.e. not based on existing but on potential production practices. Possibly, different designs and/or scenarios could be included to compare their influence on future GHG emissions and LUC.

In addition to the unequal coverage of production systems, also regions are covered unequally in existing case studies. Almost all studies investigate dairy and beef production in either Europe, North America, Oceania or Brazil. While detailed studies on cattle production in developing countries are lacking, GLOBIOM shows that there are significant differences in the GHG balance and land occupation between and within developing regions. Also, it is found that cattle production in developing countries contributes considerably to land use change. This should be investigated in more detail. It is therefore highly recommended to dedicate more studies on developing countries and collect more data for these regions.

Based on the bottom-op studies from literature, GHG reduction potentials of 1% to 26% were found for intensification of dairy cattle in Europe. It is, however, difficult to specify under which conditions the reductions would be low or high. This is because the intensification practices applied vary between papers. Also, the studies provide limited detail about these practices and how they influence the results. Therefore, more research is required into the different intensification practices and their impact on the GHG emission reduction potentials.

As mentioned in Section 2, the majority of bottom-up studies conduct modelling exercises instead of actual experiments. The applied models include cattle production systems that are considered to represent the most common systems in the region (see e.g. de Léis et al., 2015). However, due to the actual variety in production systems and uncertainties about input data (e.g. feed intake) (de Léis et al., 2015), model outcomes may only give a limited insight in the actual situation. It is therefore recommended to collect more farm data and to conduct more experiments.

Based on the description of the management system in the bottom-up studies, the classification to one of the three production systems was not always clear, especially for dairy. Many studies use production system classifications which are different from the classification applied in the present study, e.g. average dairy system or improved natural grass system. Other studies classify the system as pasture-based or confinement system, while the present study categorizes it as mixed based on the detailed system description. For dairy, the impact on the results is expected to be limited as the differences in GHG emissions within and between pasture-based and mixed systems in developed countries are relatively small. However, for beef production, especially in Latin America, the results are more likely to change when the system classification would be altered. Because of the large variation in production practices, the classification system applied in the present study is appropriate for models, but less suitable to apply to case specific studies. Although this cannot be solved easily, a first step for improvement could be to further develop the definitions of the different production systems. These definitions could, for example, include (region and climate specific) qualifications about the time spent at pasture and the amount of grass, crops and concentrates in the diet.

4.2. LUC

Although the importance of LUC for the GHG emission balance of cattle production is widely recognized among scientists, LUC has not been included in most bottom-up studies because of conceptual and methodological limitations (Dalgaard et al., 2008). One of the limitations is insufficient or unavailable information related to LUC (Ruviaro et al., 2014). For example, the origin of feedstuff and the affected ecosystem are often unknown (Hörtenhuber et al., 2014). Nevertheless, including LUC in bottom-up studies is valuable because it allows assessing region specific impacts and trade-offs of different practices such as organic and conventional production. It is especially interesting to include LUC in LCA studies because these do not only include GHG emissions, but also consider effects on other impact categories like water consumption. The very few studies that include LUC consider different aspects, e.g. on-farm LUC due to rotation between crop- and grassland and/or LUC related to imported feeds (Bartl et al., 2011; Belflower et al., 2012; Bonesmo et al., 2013; Hörtenhuber et al., 2010; Nguyen et al., 2012). Also, studies apply different methods to calculate LUC-related emissions and results can vary significantly depending on the selected approach (Flysjö et al., 2012). Attempts are made to develop more uniform methods that can be widely applied, but there is no consensus yet on how to account for LUC-related emissions in bottom-up (LCA) studies (Flysjö et al., 2012; Hörtenhuber et al., 2014).

Using global models for the assessment of LUC is the only way to apply a uniform method for assessing global LUC and comparing regional results. The advantage is that it provides a consistent framework where agricultural production and land use are correctly balanced across all regions, through direct occupation of land, or through indirect effects as a result of feed consumption and international trade. Also, effects of varying important parameters or policy assumptions can easily be tested. A disadvantage is the level of uncertainty on some data inputs such as land cover or grassland productivity. In addition, some limitations for assessing LUC in bottom-up studies also apply to models. First, the models apply different approaches, e.g. with regard to what causes and types of LUC are included (Gerber et al., 2013, see e.g. Valin et al., 2013a). Second, as illustrated in the example of indirect land use change studies for biofuels (Wicke et al., 2012), the variety of approaches for assessing LUC and parameterisation across models lead to significant ranges of uncertainty for LUC estimates. As both bottom-up studies and global models have advantages and disadvantages to investigate LUC, it is recommended that both approaches are used complementary to each other. In all cases, the methods and underlying assumptions should be explained clearly and documented transparently so that these can be taken into account when comparing the results (Flysjö et al., 2012).

4.3. Realizing intensification pathways in practice

Our analysis suggests that it is possible to significantly reduce GHG emissions through intensification of cattle production in developing regions. However, several issues exist that constrain intensification and the realization of emission reductions in these areas. For example, there may be regional factors related to climatic, topographic and soil characteristics which constrain pasture and crop productivity (de Léis et al., 2015; Steinfeld et al., 2006b). Overcoming these constraints is often technically difficult and costly (Steinfeld et al., 2006b). In addition, the presence of a (national or international) market and access to this market are considered important drivers for the development and intensification of cattle production systems (Gerssen-Gondelach et al., 2015; Steinfeld et al., 2006b). Market access is not only important to sell products, but also to purchase feeds when the local feed availability is limited (Steinfeld et al., 2006b). However, due to a lack of infrastructure, market access is often limited in developing regions. Finally, to overcome these kind of technical and economic constraints, large investments are needed (Gerssen-Gondelach et al., 2015; Steinfeld et al., 2006b). Therefore, realizing intensification of cattle production systems in developing countries requires a region-specific approach that targets both regional difficulties and opportunities. It is considered that governments and agricultural policies play an important role in the implementation of such a strategy, e.g. by providing subsidies for the adoption of new technologies, investing in R&D and creating suitable market conditions (Gerssen-Gondelach et al., 2015).

5. Conclusions

This study reviewed and analysed the GHG emissions and land occupation of dairy and beef production in different world regions in order to compare the impact of intensification within one production system (pasture, mixed or industrial) and of transitions to another system. To this end, the study assessed the results of bottom-up studies for dairy production in Europe and beef production in North America and Brazil, data for nine world regions from Herrero et al. and results from GLOBIOM for the same world regions.

Based on the data for dairy in developed regions, minor to moderate reductions in cradle to farm gate emissions can be realized by both intensification within one system and system transitions. In developing countries, more significant differences exist in the GHG balance of dairy production, both within pasture-based and mixed systems and between these two production systems. A great potential to reduce emissions is especially found for intensification within the pasture-based system.

For beef production, it is found that in all global regions the difference in emissions within and between beef production systems is larger compared to dairy production. Often, considerable GHG reductions can be attained in both developing regions and some developed regions through intensification within the pasture-based system (through adoption of best practises available). Also, the additional GHG reduction potentials of transitions from pasture-based to mixed systems compared to intensification within pasture-based systems, as well as the GHG mitigation potentials of intensification within mixed systems are considered larger for beef than for dairy.

Although significant GHG emission reductions can often be attained by intensification within pasture-based systems, moving to the mixed system is an important strategy to significantly reduce land occupation and mitigate land use change and associated emissions. In developing regions, especially Sub-Saharan Africa and Latin America, land use change mitigation is often the most important strategy to reduce GHG emissions from dairy and beef production.

While the largest challenges and also the greatest potentials to mitigate GHG emissions are found in developing regions, studies in the literature focus on cattle production in developed countries. Therefore, more studies and data collection should be dedicated to developing countries. In addition, industrial production systems are currently not included in GLOBIOM and only assessed in a limited number of case studies. However, because of the increasing importance of reducing GHG emissions and LUC caused by the cattle sector, it should be investigated what role industrial production could play in the future. Finally, it is recommended to further investigate LUC for livestock production and associated emissions. Following these directions would help improve the understanding of the GHG emission performance of cattle production systems. The insights gained can be used to design strategies for future sustainable developments in cattle production.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2017.02.012.

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