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Mitigation of enteric methane emissions from global livestock systems through nutrition strategies

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Abstract Enteric methane (CH_4) generated in the gastrointestinal tract of ruminant represents the source of the greatest direct greenhouse gas (GHG) released from the livestock sector. We evaluated the global potential reduction of enteric CH_4 emissions released from dairy cattle through amendment of their traditional diets in 183 countries aggregated to 11 regions. Amending dairy cattle diets involves increasing the concentration of lipid (up to 6 %) and decreasing the concentration of fiber, without affecting the total gross energy intake (GEI). Enteric CH_4 emissions were calculated by using a mathematical model developed to include dietary intervention. In 2012, we found a global potential reduction of 15.7 % of enteric CH4 emissions from dairy cattle. The highest potential reduction per unit of milk produced occurs in Africa followed by South America and Asia (55, 46 and 34 %, respectively). The amended diets proposed here, mostly affect the regions in which demand for animal source protein will be greatest in the future. Because lipid supplementation may result in an indirect effect on CH_4 and nitrous oxide (N_2O) emissions from manure management, they were also estimated. Methane emissions from manure management would decrease by 13 %, while N_2O emissions would increase by 21 % due to diet amendment. On balance, the total potential reduction of GHG emissions through diet amendment was 104 $MtCO_2eq$ annually. Moreover, amending diets would increase global milk production by 13 %. This study evaluated a global potential reduction of GHG emissions directly released from dairy cattle, however, future advancements dealing with the analysis of the upstream emissions associated to these diet changes are needed.

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1 Introduction

The importance of feeding the growing population while minimizing environmental impacts of livestock production has been given significant attention over the last decade (Steinfeld et al. 2006; Golub et al. 2012; Eisler et al. 2014). Enteric CH_4 generated in the gastrointestinal tract of ruminants represents the greatest direct GHG released from the livestock sector and the single largest source of anthropogenic CH_4 at a global level (EPA 2012). About 75 % of total CH_4 emissions from livestock comes from cattle and this is expected to increase in the next decades, especially in developing countries (Tubiello et al. 2013). Over the last five decades, global enteric CH_4 emissions from dairy cattle grew by 12 %, with increases of 211 % in developing countries and decreases of 48 % in developed countries, thus highlighting a different contribution and a potential for reduction at a global level (Caro et al. 2014a). Interest in combating climate change has resulted in search for mitigation options to reduce GHG emissions from dairy cattle worldwide.

Various CH_4 mitigation strategies for dairy cattle have been studied (Knapp et al. 2014). Supplementation of traditional diets with lipids is one of the most promising mitigation strategies due to its effectiveness in reducing CH_4, environmental safety, and animal health (Hristov et al. 2013). Decreasing fiber (neutral detergent fiber, NDF) proportion, while increasing the amount of crude fat (ether extract, EE) in dairy diet reduces enteric CH_4 emissions (Granger et al. 2008; Jordan et al. 2006; Johnson and Johnson 1995). Generally, in the traditional diets, soybean products and are the most common high concentrated fat products used for feeding dairy cattle (Granger and Beauchemin 2011) whereas forages are the main source of fiber, especially in extensive or semi extensive production systems (Knapp et al. 2014). Decreasing the concentration of fiber in the traditional diets will result in a reduction of the total GEI; however, supplementing lipid can mitigate the reduction, which also may potentially reduce CH_4 production. Inclusion of lipids in animal diets may also depress feed intake and consequently animal productivity, therefore, it is recommended for the total fat not to exceed 6 to 7 % of the diet dry matter (Beachemin et al. 2008a; NRC 2001). To quantify the effect of diet composition on CH_4 production, several prediction equations were developed (Kebreab et al. 2008; Moares et al. 2014; Ellis et al. 2007). Most of the prediction equations have been used at a cow or farm level, but they have not been used to quantify global CH_4 emissions and associated mitigation potential. A global analysis dealing with the potential mitigation of enteric CH_4 from dairy cattle using the best available dietary solution to date is essential for assessment of effectiveness of environmental policies and international treaties.

The present study is unique in developing a spatially disaggregated, biologically consistent, global analysis, evaluating the potential reduction of enteric CH_4 emissions released from dairy cattle when traditional diets are amended. The amended diets have a greater lipid (up to 6 %) and lower fiber contents. In amending the diet, the total GEI was kept constant. Methane emissions were estimated using a CH_4 prediction model developed to assess effect of diet on enteric CH_4 emissions. The model incorporates the positive relationship between CH_4 emissions and energy intake (GEI) and fiber (NDF) and negative effect of lipids (EE) on emissions. The present study shows the potential annual reduction of enteric CH_4 for most of the world, namely183 countries aggregated in 11 geographical regions with the reference year being 2012. Because animal productivity is heavily influenced by diet composition (Schroeder et al. 2004), milk production from amended diets in each region was evaluated. Moreover, lipid supplementation may result in an indirect effect on CH_4 and nitrous oxide (N_2O) emissions from manure management (Montes et al. 2013), so they were also estimated. Results show areas of more effective potential reduction and the main drivers in the specific diets. Although, results presented in this paper are valid in a reduced system that not includes the production of feed and relative GHG emissions, they advance the examination of CH_4 emissions mitigation strategies and regulatory policies at regional level.

2 Method

2.1 CH_4 prediction equation

To estimate national enteric CH_4 emissions for traditional and amended diets, we used a model developed by Moares et al. (2014). The authors developed a model from 1111 observations and assumed that enteric CH_4 emissions are correlated not only with the amount of feed consumed but also nutrient composition of the diet. They used a Bayesian framework in which parameters were estimated by Markov Chain Monte Carlo methods. Because the aim of this paper was to evaluate the potential enteric CH_4 reduction due to the supplementation of traditional dairy cattle diets with lipids, the model that included diet characteristic such as NDF, EE and GEI was used (Eq. (1) from Moares et al. 2014). Enteric CH_4 emissions in each country analyzed for traditional and amended diets were then calculated:

$$CH4 = 0.225(0.713) + 0.042(0.001) \times GEI + 0.125(0.015) \times NDF - 0.329(0.094) \times EE \quad (1)$$

CH_4 and GEI are expressed as MJ head^{-1}d^{-1}. Neutral detergent fiber (NDF) is fiber content of the diet whereas ether extract (EE) represents the lipid content of the diet. Both are expressed as percentage of the total dry matter. The estimated MJ of CH_4 are converted to kg of CH_4 using a conversion factor of 55.58 MJ kg^{-1} (EPA 2014). To estimate the total emissions in each country in 2012, the average number of animals was taken from FAO database (FAO 2015). The average number of animals provided by FAO refers to lactating cows, producing milk annually.

2.2 Traditional and amended diets

The composition of traditional diets with specific ingredient contents in each region is provided in Supplementary Data (Table S3–S13) as well as the specific parameters (Table S14–S24) used in this paper. For the 11 regions, average traditional diets were taken from the literature (see Supplementary Data, table S1). The key parameters used in this study to predict enteric CH_4 emissions from feeding traditional and amended diets in each region analyzed is given in Table 1. All the ingredients associated with each traditional diet in each region are expressed in kg dry matter head^{-1} day^{-1}. For each ingredient we calculated the GEI (MJ head^{-1} day^{-1}) and to convert dry matter intake to GEI, we used the gross energy content of each ingredient provided by RFES (Beyer et al. 2003). By summing the GEI relative to each ingredient, the total GEI for each diet in each region was calculated (Table 1).

The total NDF and EE contents for each ingredient (expressed as NDF proportion and EE in 1 MJ of GEI) were taken from feed tables published by NRC (NRC 2001). For further details, the concentration of NDF and EE for each ingredient in each region is presented in Supplementary Data (Table S14–S24). The total concentration

Table 1 Dry matter intake (DMI), gross energy intake (GEI), fiber (NDF) and lipid (EE) contents of traditional and amended diets

Region	Traditional DMI (kg DM head^{-1} d^{-1})	GEI (MJ head^{-1} d^{-1})	NDF (%)	EE (%)	Amended DMI (kg DM head^{-1} d^{-1})	GEI (MJ head^{-1} d^{-1})	NDF (%)	EE (%)
OCE	15.1	269	45.9	3.2	14.4	269	42.2	6
SAM	10.0	179	48.1	2.9	9.6	179	30	6
NAM	19.4	348	51.8	3.4	18.7	348	44.9	6
AFR	6.6	117	36.1	3	6.4	117	26.6	6
ASI	11.1	199	54.5	3.7	10.6	199	44.6	6
MEA	6.4	117	33.4	4.1	6.2	117	28.4	6
SEE	17.1	301	54.1	3.5	16.8	301	50.4	6
NWE	16.2	284	55.2	3.2	15.7	284	53.7	6
SWE	18.2	326	47.6	3.3	17.9	326	44.9	6
CEE	18.1	324	47.2	3.7	17.1	324	37.6	6
NEE	14.3	256	52.5	3.1	14.0	256	47.8	6

of fiber in each diet (MJ head^{-1}day^{-1}) was evaluated as ratio between the total energy (MJ) of fiber and the total GEI (MJ). The same procedure is applied for EE for evaluating the total lipid content in each region.

For the 11 regions analyzed, the amended diets were obtained by modifying the traditional diets with the aim to: (i) increase fat content in the diet to reach 6 %, (ii) decrease high fiber ingredients, and (iii) keep the GEI constant. As fat content increased, the GEI also increased, therefore, fiber content, especially from forage sources was reduced until the GEI was the same as the traditional diet. Table 1 shows the percentage of NDF and EE as well as the total GEI used in this paper for traditional and amended diets in each region analyzed. Finally, Eq. (1) was also been applied for amended diets.

2.3 Indirect effects estimation

Because animal productivity is influenced by diet composition, the difference of milk production in regions of traditional and amended diets was estimated using a ration formulation software (see Supplementary Data for more details).

Although greenhouse gas emissions from dairy cattle result primarily from the digestive processes (CH_4 from enteric fermentation), other CH_4 (anaerobic decomposition of manure) and N_2O (nitrification/denitrification of the organic nitrogen in the manure and urine) emissions from dairy cattle occur (FAO 2009). Therefore, lipid supplementation may result in an indirect effect on CH_4 and N_2O emissions from manure management (Montes et al. 2013). Methane emissions from manure management were estimated using a Tier 2 method presented in IPCC (IPCC 2006; see Supplementary Data for more details about estimation of CH_4 emissions from manure management). Nitrous oxide emissions from manure management were estimated by following a Tier 1 method described in IPCC as well (IPCC 2006). The nitrogen excretion in each region was obtained from the prediction equation presented in (Reed et al. 2015; see Supplementary Data for more details about estimation of N_2O emissions from manure management).

3 Results and discussion

The present results are aggregated into 11 regions representing South America (SAM), North America (NAM), Africa (AFR), Middle East (MEA), Asia (ASI), Oceania (OCE), North Western Europe (NWE), North Eastern Europe (NEE), Central Europe (CEE), South Western Europe (SWE) and South Eastern Europe (SEE). Details of country groups and specific assumptions for regional aggregations are presented in the Supplementary Data (Table S1–S2 and Fig. S1–S2) as well as detailed results of enteric emissions in each of the 183 countries (see Supplementary results). In the present study, CH_4 and N_2O emissions are expressed as carbon dioxide equivalent (CO_2eq) emissions using global warming potentials of 28 and 265, respectively, based on IPCC (IPCC 2013).

According to IPCC (2013) in the present study, results for CH_4 and N_2O emissions are expressed as carbon dioxide equivalent (CO_2eq) emissions using global warming potentials of 28 and 265 (no climate feedback), respectively, based on IPCC (IPCC 2013). On balance, each region could potentially reduce its direct GHG emissions from dairy cattle by amending diets. Globally, 97.5 MtCO_2eq and 9 Mt CO_2eq were saved from enteric- and manure-related CH4 respectively, whereas we recorded a slight increase in N2O from manure management (2.5 Mt CO2eq). The total balance of emissions reduced by amending diets is considerable (104 MtCO_2eq reduced annually).

When the climate-carbon feedback for non-CO_2 gases is included the GWP of CH_4 and N_2O are higher ($GWP_{CH4} = 34$ and $GWP_{N2O} = 298$, IPCC 2013). According to these GWP values, CH_4 from enteric fermentation and manure management would be reduced of 118.3 Mt CO_2eq and 11 Mt CO_2eq respectively, whereas N_2O emissions from manure management would increase of 2.8 Mt CO_2eq.

3.1 Global potential reduction of enteric CH_4 emissions

The present analysis shows a wide range of potential emission reduction estimates at regional levels (Fig. 1). In 2012, 34 MtCO_2eq were reduced in ASI, 27 MtCO_2eq in SAM and 19 MtCO_2eq in AFR (34, 26 and 18 % of global reduction, respectively). In developed regions such as Europe (EUR), NAM and OCE, the emission reduction was much smaller (10, 3 and 2 % of global reductions, respectively). By comparing enteric CH_4 emissions estimated for traditional and amended diets, the largest percentage reduction occurred in SAM (−25 %) and AFR (−24 %). In these regions the amended diets were the most effective in terms of total CH_4 reduction. In NAM and EUR, the percentage reduction was lower than other regions (−8.5 % for both). However, in CEE the potential reduction was about 12 %. Although in MEA, 7 MtCO_2eq can be potentially reduced (7 % of contribution to the global reduction), the amended diet in this region showed a 15 percentage reduction compared with a traditional diet. A common effect for all lipid sources is that, unlike other feed constituents, they largely escape digestion in the rumen (Doreau and Chillard 1997). Consequently, the decrease in organic matter digested in the rumen leads to a decrease of CH_4 production (Beauchemin et al. 2008a, b). In amending diets, we show a global reduction of about 15 % of CH_4 emissions from enteric fermentation and ASI and SAM represent the regions in which the total reduction is more substantial (Fig. 1). It should be noted that the reduction presented in Fig. 1 is based on extensive quantities (total emissions reduced in each region/country in 2012), therefore, some variables such as number of cows may directly affect final outcomes. However, the results showed in Fig. 1 are relevant because they assess the impact of amended diets on global

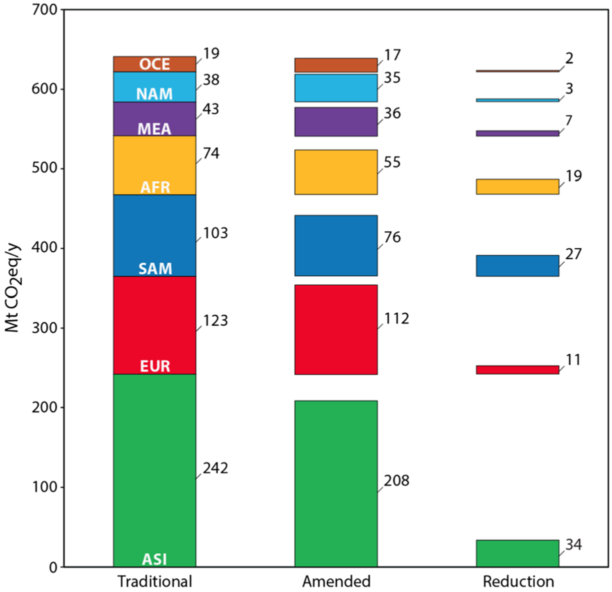

Fig. 1 Emissions (expressed as Mt CO_2eq) from traditional and amended diets and emission reductions in each region analyzed. The 5 European regions (NEE, CEE, NEW, SWE, SEE) are aggregated to Europe (EUR) to aid clarity

reduction of enteric CH_4 released to the atmosphere, thus focusing attention where most gains can potentially be made.

The potential reduction of enteric CH_4 emissions per kg of milk produced in each region was also evaluated (Fig. 2). Figure 2 highlights that AFR had the highest potential reduction of enteric emissions per kg of milk produced (0.8 kgCO_2eq reduced per kg of milk produced, resulting in reduction of 55 %) followed by SAM and ASI (0.37 and 0.32 kgCO_2eq reduced per kg of milk produced, resulting in reduction of 46 and 34 %, respectively). NAM and EUR were the regions with the lowest potential reduction per kg of milk produced (0.07 kgCO_2eq reduced per kg of milk produced in both regions) reducing their emissions per kg of milk produced by 18 and 16 %, respectively (Fig. 3). Both MEA and OCE regions had moderate potential reduction per kg milk produced (0.24 and 0.16 kg CO_2eq reduced per kg of milk produced, resulting in reduction of 32 and 30 %, respectively). Overall, when diets are amended, enteric CH_4 emissions per kg milk produced were reduced across all regions.

The greatest reduction of emissions occurred in India, Brazil, and China (15.9, 7.2 and 4.4 MtCO_2eq, respectively; Fig. 3a). Ethiopia and Tanzania were the African countries with the

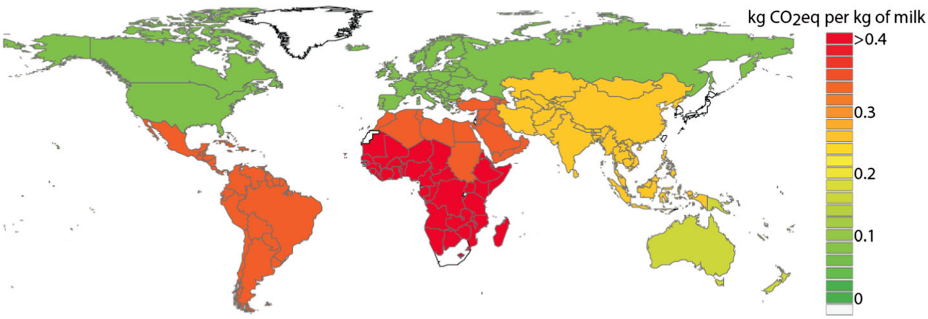

Fig. 2 Map of the potential reduction of equivalent CO_2 emissions per kg of milk produced (kg CO_2eq kg $milk^{-1}$)

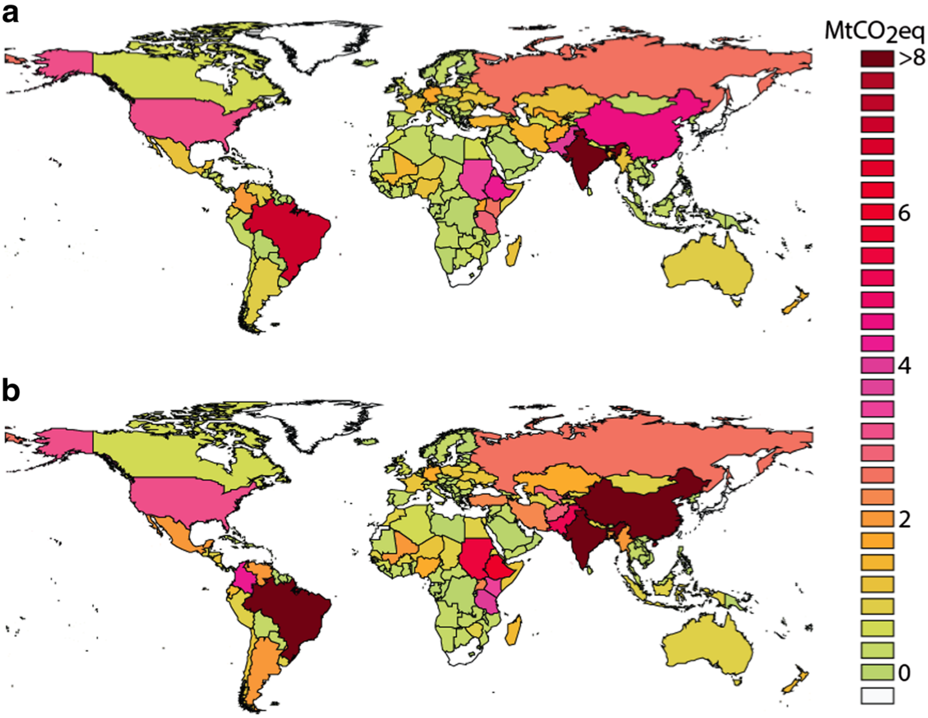

Fig. 3 Map of the total potential reduction of GHG emissions (Mt CO_2eq) occurring when amended diet were adopted. Figure 3a shows the reduction in 2012. Figure 3b shows the reduction in 2050 on the basis of predicted livestock population

greatest emission reduction (4.2 MtCO_2eq and 2.8 MtCO_2eq, respectively) followed by Kenya (2.3 MtCO_2eq) and Uganda (1.4 MtCO_2eq). However, other countries in AFR, ASI, and SAM were less influenced by amended diets (Fig. 3a). Russia (about 2.3 MtCO_2eq) and Germany (about 1.5 MtCO_2eq) represented the European countries with the largest reduction. In the rest of the EUR region, the reduction was marginal. By supplementing the amended diet, the US can potentially reduce 2.9 MtCO2eq, resulting in a reduction of 9 % of its dairy related enteric emissions whereas in Canada (0.2 MtCO_2eq), the potential reduction was lower (Fig. 3a). In MEA, Sudan can potentially decrease emissions by 3.3 MtCO_2eq whereas in OCE, New Zealand can potentially reduce 1.2 MtCO_2eq by using amended diets.

Predicted global livestock populations provided by (Alexandratos and Brunsma 2012) are used to analyze the impact of amended diets for potential reduction in enteric emission in 2050 (Fig. 3b). The potential for emission reduction in 2050 was greatest in developing countries but others were marginally impacted. Particularly, ASI and SAM were the regions with the greatest increase in potential reduction. In 2050, by using the amended diet, Brazil and China could potentially reduce 17.9 and 8.2 MtCO_2eq, respectively, because of a substantial increase in their expected dairy cattle populations. A less remarkable reduction also occurred in AFR and MEA (Fig. 3b). In developed regions, such as EUR, NAM and OCE, the potential reduction remained unchanged because dairy cattle population is not expected to increase in these regions.

When amended diets are used, the effect of lipid supply and the associated potential reduction of CH_4 emissions vary across the regions because they depend on the type of diet. The greatest potential reduction occurs in regions generally characterized by extensive systems (Fig. 2). Moreover, we observe that in these regions decreasing fiber content affects CH_4 mitigation more than increasing lipid content (see Supplementary Data, Figure S3). Extensive systems occur mainly in semi-arid zones, with some in sub-humid zones such as SAM, AFR, MEA and ASI, where use of low quality native forages sources are common. Moreover, in these regions, the demand for dairy products is expected to rise in the next decades with concomitant increase in dairy cattle populations (Herrero et al. 2009). Enteric CH_4 will also rise with increased cow numbers; therefore, diet amendments are expected to have the greatest potential impact in these regions in the next few decades (Fig. 3b). Because in extensive or semi extensive production systems the animals are kept free-range for part or all of their production cycle, forages are their main source or carbohydrates (mainly polysaccharides) whereas in more intensive systems grain-based concentrates provide the required dietary energy (Knapp et al. 2014). As greater proportion of forages are replaced by lipid, the potential impact in reducing enteric CH_4 becomes greater compared to traditional diets with more concentrates. Reducing fiber in the diet will decrease total GEI; however, supplementing lipid can mitigate the reduction, which also reduces CH_4 production. For this reason, enteric CH_4 reduction is greater for hay based diets (i.e. Brazil) than for corn silage diets (i.e. European regions). Moreover, such effect is amplified when the total GEI of regions is lower. We conclude that the potential CH_4 reduction is negatively correlated with GEI but is positively correlated with fiber content.

3.2 Indirect effects

The animal productivity is influenced by diet composition. Lipid supplementation may also result in an indirect effect on CH_4 and N_2O emissions from manure management (Montes et al. 2013). In this section we present results showing the indirect effects of amended diets.

3.2.1 Animal productivity

In addition to potential enteric CH_4 reduction, increases in milk production are also expected with amended diets, which could bridge the gap between demand and supply (FAO 2011). Using amending diets, this analysis shows a potential global milk production increases of about 13 % and for each region except for NEE milk production per cow would potentially increase (Fig. 4a). Figure 4a shows that, although the traditional diet in AFR resulted in the lowest milk productivity (3 kg per cow per day), it represented the region with the greatest

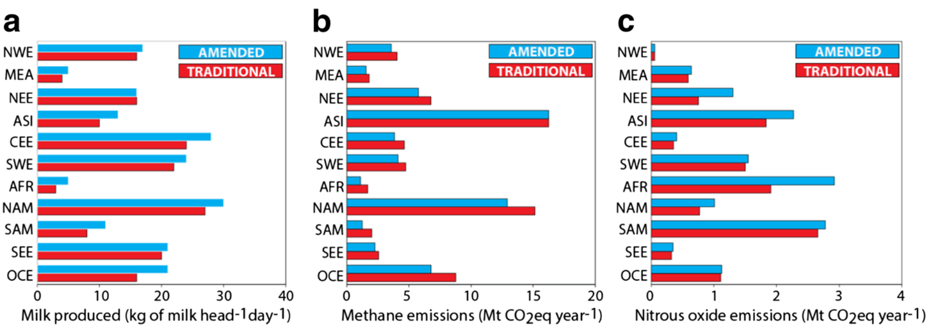

Fig. 4 Indirect effects of traditional and amended diets. Potential productivity of dairy cattle expressed as amount of milk daily produced (kg milk head^{-1}day^{-1}) for traditional and amended diets (**a**). Total CH_4 emissions (Mt CO_2eq year^{-1}) from manure management for traditional and amended diets (**b**). Total N_2O emissions (Mt CO_2eq year^{-1}) from manure management for traditional and amended diets (**b**)

potential increase in milk production if amended diet were used (67 %). Regions with significant improvement include SAM, OCE and ASI (38, 31 and 30 %, respectively). The NAM region had the greatest milk productivity using traditional diet (30 kg per cow per day), which limits additional increases in productivity with amended diets (11 %). In EUR, results for dairy productivity were slightly contrasting. The European region with the greatest milk productivity was CEE (24 kg per cow per day) and it also had the greatest potential increase in milk production if amended diet was used (17 %). The lowest milk production in EUR using traditional diet was in NWE and NEE regions (16 kg per cow per day). However, NWE had 6 % potential to increase milk production using amended diet whereas NEE was the only region analyzed in which milk production remained constant.

The greatest increase in milk production occurs in extensive and semi extensive production systems because substituting forages with more digestible fiber sources improves energy utilization for milk production and less of that energy is lost as heat and CH_4 (Moraes et al. 2015). Generally, in pasture-based systems milk production is lower than feeding total mixed rations because in grazing conditions energy intake is the most limiting nutrient for milk production (Rabiee et al. 2012). In this context, the present study provides an additional knowledge concerning the utilization of lipids as strategy for increasing the milk production, especially because the supplementation of lipid sources can have several advantages with respect to protein and carbohydrates utilization (Doreau et al. 2014). For example, it has been highlighted that supplementation of lipids increases the energy density of the diet and reduces the risk of rumen acidosis (Palmquist 1988) and it may improve quality of dairy products for human health (Parodi 1999).

3.2.2 Methane emissions from manure management

An additional reduction of CH_4 emissions from manure management occurs with diet amendment (Fig. 4b). Globally, CH_4 emissions due to manure management of amended diets decreased by 13 % resulting in a decrease of 9 $MtCO_2$eq (see Supplementary results for detailed results of CH_4 emissions in each of the 183 countries). Methane emissions would decrease in all regions if amended diets were adopted except in ASI (Fig. 4b). The greatest decrease in CH_4 emissions occurred in SAM, AFR and OCE (−38 %, −34 % and −23 %). CEE was the European region that mostly reduced its CH_4 emissions (−17 %). For amended diets, CH_4 emissions in NAM decreased by 15 %, whereas ASI was the only region analyzed in which CH_4 emissions remained constant.

The reduction of CH_4 emissions from manure management is less evident compared to enteric CH_4 emissions because it is more influenced by storage and temperature. Assuming same storage and temperature conditions, reduction of CH_4 emissions from manure management is due to the different percentage of digestibility of the traditional and amended diets. According to IPCC (2006), the percentage of digestibility is higher when animals are fed with more concentrate-based diets and lower when animals are fed with more forage-based diets. Therefore, the traditional diets (more forage-based diet) are less digestible than amended diets, resulting in a higher volatile soil excretion (see Supplementary Data, Table S25) and emission factor.

3.2.3 Nitrous oxide emissions from manure management

Although global enteric emissions could be potentially reduced if amended diets were used (Fig. 1), an indirect increase of N_2O emissions due to increased nitrogen excretion in each region occurred (Fig. 4c). Globally, N_2O emissions due to manure management of amended diets increased by 21 % resulting in an increase of 2.5 $MtCO_2eq$ released to the atmosphere (see Supplementary results for detailed results of N_2O emissions in each of the 183 countries). The greatest increase in N_2O emissions occurred in SAM, CEE and ASI (73, 53 and 31 %, respectively; Fig. 4c). In the remaining European regions and MEA N_2O emissions were less influenced by amended diets. Nitrous oxide emissions in NAM and AFR increased by 24 and 14 %, respectively.

The increase of nitrogen excretion is mainly due to ingredients with high fat content generally having a greater protein content than forage based ingredients (see Supplementary Data, Table S3–S13). For example, soybean products contain crude protein content of 40 % or more (NRC 2001). Consequently, the greatest increase in nitrogen excretion, which potentially increases N_2O emissions occurs in SAM, where soybean products are mostly supplemented in amended diets. It should be noted that some ingredients with high fat contents have a lower protein than others. For instance, cottonseed products have much lower protein content than soybean products. For this reason, in regions where cottonseed products are mostly supplemented (such as NWE and MEA) indirect effect of N_2O emissions is less relevant.

4 Strengths and limitations

Results obtained for traditional diets represent a comprehensive and detailed estimate of global enteric emissions released from the dairy sector in 2012. Dairy cattle, especially in developing countries, represent a remarkable source of enteric CH_4 (Fig. 1). The variation among regions is to large extent explained by their contribution to production, their production systems and management practices. Dietary preferences are a strong driver of emissions. In the last two decades, increase in cow's milk consumption in developing countries, has significantly outpaced that of developed countries, highlighting country-level differences (Gerosa and Skoet 2012). However, dairy foods are an important source of calories as well as protein and micronutrients, especially in developing countries (Knapp et al. 2014). In NAM, emission intensities for milk is lower than in Western Europe because the region generally relies on feed with lower emission intensity whereas ASI is at the same level as NAM but its protein production is half what is produced in those areas (Gerber et al. 2013). At present time, more opportunity exists in developing countries to reduce enteric CH_4 through combinations of genetic selection (Knapp et al. 2014) and other management approaches (FAO 2010). Several factors may increase the efficiency of milk production thus reducing CH_4 emissions per ton of cow's milk produced: i) the reproductive efficiency, ii) the animal health and iii) the better feed quality (Opio et al. 2013). All these factors combine to result in higher productivity and lower emission intensity. The scientific basis for these improvements already exists; achieving them depends on economic and policy implementations.

For traditional diets, our estimates are greater than those provided by FAOstat database (+23 %; FAO 2015). This is mainly due to methodological differences. The enteric CH_4 prediction equation used in the present study uses the same amount of information required by the IPCC Tier 2 method, but with substantial improvement in prediction (Moares et al. 2014). The FAOstat database uses a standardized IPCC Tier 1 method that does not consider differences in diet composition. Although the FAOstat database is more detailed in terms of regional aggregation, a recent study showed that application of a Tier 1 method involves an uncertainty of about ±44 % (Caro et al. 2014b).

Limitations in using the methodology we adopted include data collected in respiration chambers for developing models may not be representative of grazing systems and can affect emissions estimates, especially in regions characterized by extensive systems (Moares et al. 2014). Moreover the assumptions regarding the regional aggregation presented in the present study, may rationally affect the estimation of final results. In fact, existing classification schemes of global livestock production systems recognize large diversity in management practices within each region (Robinson et al. 2011). In particular, aggregation developed for ASI and SAM might involve some limitations because countries within these regions are characterized by diversity of production systems and consequently, of traditional diets (Gerber et al. 2013).

Although the benefits associated with the inclusion of lipids in dairy diets have been experimentally demonstrated (such as effectiveness, environmentally safe, safe to the animal and potentially CH_4 mitigating effect), the long-term effect of this mitigation practice is not conclusive (Martin et al. 2011; Eugene' et al. 2011). Another important factor that needs to be take into account, is the effect of lipid supplementation on milk fat content (Schroeder et al. 2004) because diet composition has been shown to affect milk quality (Knapp et al. 2014). For example, coconut oil can cause milk fat depression (Hristov et al. 2009), but results are not always consistent (Hollmann and Beede 2012). Additional studies aimed to investigate the long-term effect of lipid supplementation on enteric CH_4 reduction and the effect on milk fat content should be developed and evaluated on a whole-herd basis.

Methane emissions decrease in all regions when amended diets are adopted because more forage-based diets are less digestible than more concentrate grain-based diets (Fig. 4b). However, a recent paper claimed that when lipids reduce fiber digestibility, then more CH_4 may be emitted from the manure during storage and anaerobic fermentation (Knapp et al. 2014). According to IPCC (2006) digestibility data should be based on measured values with consideration for seasonal variation. In facts, the digestibility of forages is typically lower during the dry season. Moreover, accurate estimates of feed digestibility are also generally affected by a higher degree of uncertainty (IPCC 2006). Therefore, due to significant variation and uncertainty, digestibility coefficients should be obtained from local scientific data wherever possible.

This study shows a global reduction of 104 $MtCO_2eq$ released from dairy cattle through the supplementation of traditional diets with lipids. The changes proposed imply a transition toward a diet with a lower share of crop residues, and a lower dependence on extensive and non–managed grasslands. However, the extra production of lipids in the amended diets would increase the share of cultivated crops that are in competition with human food, thus having a potential effect on GHG emissions, such as land-use change emissions. Land-use change is estimated to contribute 9.2 % to the sector's overall GHG emissions of which 6 % due to pasture expansion and 3.2 % due to feed crop expansion (Gerber et al. 2013). Therefore additional lipid supplementation may reduce land-use change emissions associated with pasture expansion (Herrero et al. 2016), but it is also responsible for land-use change emissions associate with their production (Opio et al. 2013). Such exploration is beyond the scope of current study. The results presented in this paper are valid in a reduced system that not includes the production of feed and relative GHG emissions.

The lipid supplementation presented here, is mainly based on soybean oils. These ingredients are characterized by a nutrient content that is complementary to cereal grains such as corn and a higher concentration of fat. They fit into any type of forage-based ration, thus making these products excellent ingredients for dairy related diets worldwide (Taghinejad et al. 2009). In some vivo studies, the enteric CH_4 decrease by supplementing these ingredients has been also highlighted (Machmuller et al. 1998). Moreover, soybean supplementation results in an increase of milk productivity because it improves energy utilization for milk production by reducing the energy lost as heat and CH4. Although the supplementation of lipids potentially increases N_2O emissions from manure management, the tradeoff in terms of GHG emissions is positive. However, because soybean is mostly produced in Latin America, the growing international demand for these products can result in an increase in deforestation, whereby natural forests are cleared for agricultural production. In this context, reducing the tropical deforestation is a priority for mitigating climate change with many countries investing to protect tropical forests through projects related to REED+ (REED+). Therefore, inclusion of lipids such as soybean products may be a feasible and economic mitigation practice when they are available at regional level (Hristov 2012).

An additional economic analysis, calculating and comparing costs of traditional and amended diets would provide information for better decision making. In this context, the additional costs associated with amended diets might be mitigated by increases in milk production and environmental sustainability measures. As demand for animal source protein increases, pressures for improved productivity, and better stewardship of the environment will also increase. Therefore, countries that improve their efficiency of production and reduce environmental footprint may be better suited to create an enduring dairy sector and have a competitive advantage in the global marketplace.

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