Quantifying greenhouse gas emissions attributable to smallholder livestock systems in Western Kenya: cradle to farm gate life cycle assessment

Ndung'u, P.W.[1, 2]; Takahashi, T.[3, 4]; du Toit, C.J.L.[1]; Robertson-Dean, M.[5]; Butterbach-Bahl, K.[2, 6]; McAuliffe, G.[3]; Merbold, L.[2]; Goopy, J.P.[1, 2, 7]

[1]Department of Animal and Wildlife Sciences, University of Pretoria, 0002, South Africa
[2] Mazingira Centre, International Livestock Research Institute, P.O. Box 30709, Nairobi, Kenya
[3]Rothamsted Research, North Wyke, Okehampton, Devon, EX20 2SB, UK
[4]University of Bristol, Langford House, Langford, Somerset, BS40 5DU, UK
[5]School of Mathematics, University of New England, Armidale, NSW, Australia.
[6]Institute for Meteorology and Climate Research, Atmospheric Environmental Research, Karlsruhe Institute of Technology, D-82467 Garmisch-Partenkirchen, Germany
[7]corresponding author

Key words: quantile regression; African livestock systems; emissions intensity; greenhouse gas emissions; primary data

Abstract

Ruminants are central to the economic and nutritional life of much of sub-Saharan Africa, but cattle are now blamed for having disproportionately large negative environmental impact through (amongst other things) emissions of greenhouse gases. However, the exact mechanism behind these emissions is not well-understood and indeed accurate estimates themselves are lacking due to a paucity of reliable data. Employing individual animal records obtained at regular farm visits, this study quantified emissions intensities (EIs) of smallholder farms in three counties of Western Kenya through life cycle assessment (LCA). Crude protein (CP) was chosen as the functional unit to capture outputs of both milk and meat. The results showed that milk is responsible for 80-85% of total CP output. Farm EI ranged widely from 20- >1,000 kg CO2-eq/kg CP and median EIs were 60, 71 and 90 kg CO2-eq/kg CP for Nandi, Bomet and Nyando respectively. EIs referenced to milk alone revealed that while the median EI for Western Kenya (2.3 kg CO2-eq/kg milk) was almost twice that reported for Europe, up to 50% of farms had EIs comparable to the mean Pan- European EIs. Enteric CH4 contributed >95% of emissions and manure ~4%, with negligible emissions attributed to input to the production system. Collecting data from individual animals on smallholder farms enabled the demonstration of an extremely heterogenous EI environment amongst smallholder farms and provides clear indicators on how to achieve low EIs in these environments. Contrary to some current belief, our data show that industrial- style intensification isn't required to achieve low EI, and that this can be achieved in a low input environment. Enteric CH4 production overwhelmingly drives farm emissions in these systems and, as this is strongly collinear with nutrition and intake, effort will be required to achieving an "efficient frontier" between feed, emissions and animal productivity.

Introduction

Livestock plays an important role in social and economic growth of Africa (Herrero *et al.,* 2013). Driven by steady increases in population, gross domestic product (GDP), and household incomes (Steinfeld *et al.,* 2006), demand for livestock products is rapidly growing (Thornton, 2010), with consumption of beef and milk forecast to increase by 261% and 399% respectively, between 2010 and 2050 (FAO, 2017). At the same time, supply of livestock products in Africa is constrained by competition with other sectors for scarce natural resources, suboptimal animal husbandry practices, and unreliable availability and quality of feed (Thornton 2010; Nkonya *et al.,* 2016). Environmentally, these challenging conditions have resulted in an unusually high proportion of regional anthropogenic greenhouse gas (GHG) emissions attributed to animal agriculture, namely at 25% compared to the global average of 14.5% (Gerber *et al.,* 2011; Gerber *et al.,* 2013).

To date, the exact mechanism behind these high livestock emissions in the sub-Saharan African region — or the accuracy of these estimates for that matter — is not clearly understood. This is primarily the case as most GHG inventories in Africa have been collated using the Intergovernmental Panel on Climate Change (IPCC) default (Tier I) emission factors (EF), an annual estimate of GHG emissions per head for each class of animals. While this approach is often necessitated by a lack of detailed field data to produce country-specific EFs, it is subject to a large degree of uncertainty in the presence of locally and seasonally variable animal phenotypes and feed baskets, two conditions that are almost always met in the local smallholder context (Herrero *et al.,* 2013; Goopy *et al.,* 2018).

Nonetheless, accurate estimation of per head EFs alone do not capture the entire variability in climate impacts across smallholder livestock farms (Goopy *et al.,* 2018; Ndung'u *et al.,* 2019), because in a production environment where production per animal also varies, a farm's overall GHG performance is better assessed by emissions intensity (EI) (Moran and Wall 2011) considering all material input into and output of the system under the life cycle assessment (LCA) method (ISO 2006). This view is particularly pertinent to agricultural systems where the presence of unproductive livestock owned for a variety of non-economic reasons has been suggested as a major cause of large on-farm emissions (Weiler *et al.,* 2014). Paradoxically, however, these systems are the ones with the greatest potential to mitigate GHG emissions simply via improved productivity, and therefore among the most important to examine in detail (IPCC 2007).

Using animal-level data collected across multiple seasons on 313 smallholder livestock farms in Western Kenya, this study elucidates the distribution of farm-level EIs as well as their determinants. Although dairy farming is the most developed agricultural sub-sector in Kenya, unintuitively it is predominantly supported by smallholders in rural areas (Muriuki 2013). In particular, Western Kenya's Central and Rift Valley highland regions produce 60% of the country's milk supply (Muriuki 2013), and their systems are representative of the wider East Africa where livestock is an integral part of mixed agriculture that has a dual purpose of domestic food production and cash generation. Thus, we developed the null hypotheses that:

i) GHG EI in smallholder livestock production systems in Western Kenya do not vary between a) farms, b) AEZs or c) regions.

ii) The contribution of meat production is unimportant to overall output from these farms as measured by crude protein (CP) production, and

iii) EIs are similar to model-based estimates reported in the extant literature.

Materials and Methods

Study Site

Data used in this study were collected from 313 smallholding farms located across three counties in Western Kenya: Nyando, Nandi and Bomet. Collectively, the study region encompasses six AEZs. For each county–AEZ combination, sample farms were selected under a randomized stratified sampling procedure and data collection comprised of five visits to each farm with a 12-month period as described in Goopy *et al.,* (2018).

A cradle-to-farm gate approach was adopted to quantify herd-level EIs associated with cattle (Figure 1). In order to eliminate the aggregation bias, or systematic underestimation of climate impacts caused by "weakest link" animals (McAuliffe *et al.,* 2018), these values were initially calculated on an animal-by-animal basis for each season and subsequently combined across seasons and then animals in that order. Although cattle data were repeatedly recorded for a period of 12 months, which constitute the temporal boundary of this study, the herd structure of each individual farm was not always at a steady state due to movement of animals in and out of the farms in the forms of sales, purchases, and temporary relocation to other farms during feed shortages. Across the entire sample, however, this effect was assumed to be largely cancelled out due to the sufficient sample size. The primary FU for the study was set as kg CP, encompassing both meat and milk production from multi-purpose cattle. We assumed that all animals sold out of study farms were sold for meat (or sold for further rearing before being on-sold for meat). Commensurably, animals purchased onto study farms were accounted for as an offset to the gross output. Thus, the total CP yield from each animal during the study period was defined as the net growth measured by the embedded CP content plus the CP content of milk produced. To estimate the CP content of meat, a dressing percentage of 52.1% was assumed based on the locally most relevant information (Muchenje *et al.,* 2008). Meat yield was set at 85% of carcass weight (Department of Agriculture and Rural Development 2016) with a CP content of 21% (Muchenje *et al.,* 2008). Edible by-products (offal) were also included in the total meat CP yield to reflect the local culinary practice. These included heart, kidneys, liver, lungs, spleen, tripe, tongue, and pancreas. The average offal yield (5.3% of LW) and its CP content (18.2%) were obtained from the literature (Nollet and Toldra 2011). In addition, FPCM (kg) (IDF, 2010) and bone-free carcass weight (kg) were adopted as auxiliary FUs to facilitate the comparison of results with single-commodity LCA studies for milk and meat, respectively. The FPCM was standardized to 4% fat and 3.3% true protein. The bone-free carcass weight was estimated using the assumptions described above.

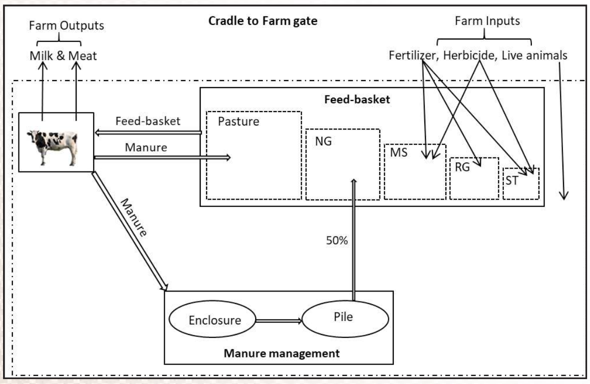

Figure 1: System boundary for life cycle assessment of smallholder farms. Squares show feedstuff in the feed- basket where the sizes demonstrate the contribution of each feed to the overall feed-basket (NG: Napier grass; MS: maize stover; RG: Rhodes grass; ST: sugarcane tops), ovals show the manure management systems. shows the flow of raw materials and where the manure is deposited and → shows the farm inputs and output.

Enteric CH_4 emissions were calculated according to the approach described in Goopy *et al.,* (2018). Composite emission factors manure left on pasture (50%), in an enclosure (Boma) (25%) and in a pile (25%) for CH_4 and N_2O manure were both estimated as weighted averages of the values locally measured under the three conditions. Annual gas-by-gas emissions attributable to each animal were converted to global warming potential (GWP) under the 100-year Global Warming Potential (GWP100) method, which assumes the characterization factors of 28 and 265 for CH_4 and N_2O, respectively (IPCC 2013). This value was next aggregated across all animals within a single farm to estimate the farm-level GWP. Finally, the corresponding farm-level EI (CO_2-eq/kg CP) was derived as the ratio between GWP and the total (net) CP output. Initial analysis of farm EIs (n = 313) identified a small number of farms across three counties (n = 25) with nil or negative CP output, resulting in aberrant (infinitely large) EIs. Additionally, a small number of farms (n=4) with positive but very low CP outputs (<3kg CP p.a.) returned extremely high EIs (>3,000kg CO_2-eq/kg CP). With the upper bound for EIs in livestock systems posited to be ~1,000kg CO_2 eq/kg CP (Gerber *et al.,* 2011), the decision was made that EIs above this value would be truncated. Similarly, the distribution of farm-level EIs was preliminarily studied under a variety of exploratory data analysis methods. As this revealed that the data were extremely right- skewed without a uniform variance, further investigations to explore the factors contributing to differences in EI were undertaken using quantile regression (Koenker and Hallock 2001). The following quantiles were used for the present analysis: 0.85, 0.75, 0.5, 0.25 and 0.1. with a model created for each of these quantiles. The explanatory variables considered include herd size, parity, average age (of cattle), milk yield, meat yield, and total GHG emissions. Fixed effects associated with counties and AEZs were also considered.

Results

Distribution of farm EIs

Median farm EIs were estimated to be 67, 66, and 128 kg CO2-eq/kg CP for Nandi, Bomet, and Nyando counties, respectively. However, the values of individual farms dramatically varied even within each county. There was also substantial variation in the frequency of occurrence of low, intermediate, and high EI farms between counties and AEZs, with Nyando having the greatest proportion of high EI farms (Figure 2).

Factors influencing farm-level EIs

Quantile regression revealed several management features that are highly influential to EI at the farm level, irrespective of the county or AEZ. Some factors were universally important, while others only at some EI quantiles. Despite the uneven contribution to total CP outputs, both meat and milk yields were significant drivers of EI across all quantiles investigated. Mean milk yield per cow, rather than milk production per farm, was found to be the most important driver of EI, with an increase in yield associated with a decrease in EI.

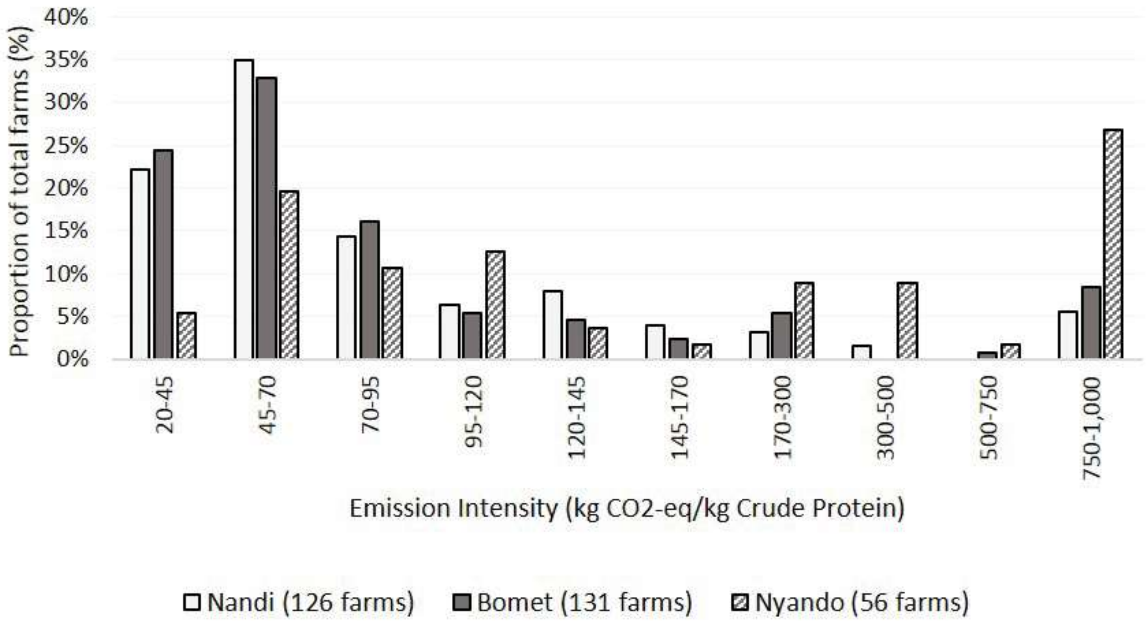

Figure 2: Distributions of farm-level emissions intensities for smallholder farms in Nandi, Bomet and Nyando

An increase in herd size was found to increase EIs for low and medium EI (high and moderate performing) farms (Q10: $\beta HS = 1.35$, $p < 0.005$, Q50: $\beta HS = 1.86$, $p < 0.01$,), whereas this tendency was not observed among high EI (low performing) farms. Although the average age of cattle was not important to EI, the proportion of females in a herd was negatively related to EI for most quantiles. The effect of calving percentage was only significant — and positive — for high EI farms ($p<0.005$). Finally, there were no clear differences in EI between AEZs, likely because the intrinsic differences were captured by other variables in the models.

Discussion

In many ways, nominal comparison of mean/median EIs between different dairy production systems obscures important findings from the present study. Firstly, our data demonstrate that meat CP makes up 15-25% of farm output across systems, and thus to ignore this would result in a substantial over-estimation of EI in smallholder farms unless emissions attributable to the 'by-product' (meat) are appropriated allocated out. Secondly, although a few studies have applied LCA to estimate EIs in African livestock systems (Opio *et al.,* 2013; Weiler *et al.,* 2014; MacLeod *et al.,* 2018; Kiggundu *et al.,* 2019), input data have been derived from a variety of secondary sources in every case, including post hoc farmer estimates, national census statistics, FAOSTAT databases, and modelling based on these secondary data. In contrast, the results reported herein are based on measurements of individual animals and actual feed baskets, providing a far clearer picture of the heterogeneity of farm-level EIs across counties and AEZs. This approach, in turn, led to the revelation that some 57%, 58% and 20% of the sample farms in Nandi, Bomet and Nyando achieved EIs comparable to European/North American intensified operations and, notably, without employing a high degree of intensification that is a hallmark of such systems. Characterization of the drivers of highly and less efficient farms has provided insights into the factors driving low EIs in smallholder farms, something unachievable in studies relying on secondary data. A curious finding of this study was the simultaneous presence of farms with very high and very low efficiencies, even between neighbouring enterprises. Prima facie, the differences between farms at the extremes of EI distribution were attributable to differences in CP output — very low EI enterprises had substantial outputs, whereas very high EI enterprises had little or in some cases no output at all in the course of the year. The absence of lactation and steady animal growth caused a small number of individual farms to demonstrate exceptionally large EIs. Between extremes of EI, where the factors affecting these values could be more clearly discerned, determinants of EI were not so readily apparent. Enteric fermentation overwhelmingly drove emissions on all farms in all regions, 96 - 97% of total GHGs attributable to this source. There are two readily identifiable causes of this difference. Firstly, the livestock systems in this study were low input in terms of fertilizers, purchased feeds and mechanization, which in intensive European farming systems account for 7 to 20% of total emissions (Opio *et al.,* 2013; O'Brien *et al.,* 2014; O'Brien *et al.,* 2015). Secondly, emissions from manure management were low as a result of a drier climate, rather than those found in Europe under which manure may comprise 5 to 9% of total emissions (Opio *et al.,* 2013; O'Brien *et al.,* 2014; O'Brien *et al.,* 2015). Examining the characteristics of farms with low EI farms provides insight into effective strategies to move smallholder farms toward a low carbon future. Enteric CH4 production overwhelmingly drives farm emissions in these systems and, as enteric fermentation is strongly linked to nutrition, intake and productivity, attention must be focused on increasing on-farm output per animal while constraining further increases in enteric CH_4 as far as possible. Our results indicate mitigation potential towards improving the productivity on a per animal basis and restructuring the herd in favour of productive females with high(er) milk outputs. This will not only contribute to reduced carbon footprint but will also likely have social and economic advantages such as increasing household incomes.

Acknowledgements

This study was funded by the International Fund for Agricultural Development (IFAD) through the research projects "Greening Livestock: Incentive-Based Interventions for Reducing the Climate Impact of Livestock in East Africa" (Grant No. 2000000994) and further supported by the German Federal Ministry for Economic Cooperation and Development (BMZ issued through GIZ) Programme of Climate Smart Livestock (PCSL). The authors further acknowledge the CGIAR Fund Council, Australia (ACIAR), Irish Aid, European Union, IFAD, the Netherlands, New Zealand, UK, USAID and Thailand for funding the CGIAR Research Program on Livestock. The authors appreciate funding from the Biotechnology and Biological Sciences Research Council (BBS/E/C/000I0320) and the South African National Research Foundation, NRF Thuthuka Grant No. TTK180419322838.

References

Department of Agriculture and Rural Development, K. Z. N. 2016. *Useful Statistics: Beef Production*. Pietermaritzburg, South Africa, Viewed at https://www.kzndard.gov.za/images/Documents/RESOURCE_CENTRE/GUIDELINE_DOCUMENTS/PRODUCTION_GUIDELINES/Beef_Production/Useful%20Statistics.pdf on 19/9/2019

FAO. 2017. Africa Sustainable Livestock 2050 – Technical Meeting and Regional Launch, Addis Ababa, Ethiopia, 21–23 February 2017. FAO Animal Production and Health Report. No. 12. Rome, Italy. viewed at http://www.fao.org/3/a-i7222e.pdf on 03/08/2020.

Gerber, P., Vellinga, T., Opio, C., and Steinfeld, H. 2011. Productivity gains and greenhouse gas emissions intensity in dairy systems. *Livestock Science,* 139; 100-108. doi: 10.1016/j.livsci.2011.03.012

Gerber, P. J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Tempio, G. 2013. *Tackling climate change through livestock: a global assessment of emissions and mitigation opportunities*: Food and Agriculture Organization of the United Nations (FAO).

Goopy, J.P., Onyango, A., Dickhoeffer, U., and Butterbach-Bahl, K. 2018. A new approach for improving emission factors for enteric methane emissions for cattle in smallholder systems of East Africa-results for Nyando, Western Kenya. *Agricultural Systems,* 161; 72-80. doi: 10.1016/j.agsy.2017.12.004

Herrero, M., Havlík, P., Valin, H., Notenbaert, A., Rufino, M. C., Thornton, P. K., . . . Obersteiner, M. 2013. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. *Proceedings of the National Academy of Sciences, 110*(52), 20888-20893. doi: 10.1073/pnas.1308149110

IDF. 2010. *A Common Carbon Footprint for Dairy. The IDF Guide to Standard Lifecycle Assessment Methodology for the Dairy Industry*. Bulletin of the International Dairy Federation 445. International Dairy Federation. Brussels, Belgium.

IPCC. 2007. Climate Change 2007: Syntehsis Report. In R. K. Pachauri & A. Reisinger (Eds.), *Contribution of Working Groups I, II and III to the fourth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC, Geneva, Switzerland, 104pp.

IPCC. 2013. Climate Change 2013: *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. . Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., 1535 pp. doi: 10.1017/CBO9781107415324.

ISO. 2006. 14040: *Environment Management - Life cycle assessment - Principles and Framework*. International Organization for Standardization, Geneva, Switzerland.

Kiggundu, N., Ddungu, S. P., Wanyama, J., Cherotich, S., Mpairwe, D., Zziwa, E., . . . Falcucci, A. 2019. Greenhouse gas emissions from Uganda's cattle corridor farming systems. *Agricultural Systems,* 176; 102649. doi: https://doi.org/10.1016/j.agsy.2019.102649

Koenker, R., and Hallock, K. F. 2001. Quantile Regression. *Journal of Economic Perspectives,* 15(4): 143-156. doi: 10.1257/jep.15.4.143

MacLeod, M., Eory, V., Wint, W., Shaw, A., Gerber, P. J., Cecchi, G., . . . Robinson, T. 2018. Assessing the Greenhouse Gas Mitigation Effect of Removing Bovine Trypanosomiasis in Eastern Africa. *Sustainability,* 10(5): 1633. doi: 10.3390/su10051633

McAuliffe, G. A., Takahashi, T., Harris, P., Orr, R. J., and Lee, M. R. F. 2018. Distributions of emissions intensity for individual beef cattle reared on pasture-based production systems. *Journal of Cleaner Production,* 171: 1672-1680. doi: 10.1016/j.jclepro.2017.10.113

Moran, D., and Wall, E. 2011. Livestock production and greenhouse gas emissions: Defining the problem and specifying solutions. *Animal Frontiers,* 1(1): 19-25. doi: 10.2527/af.2011-0012

Muchenje, V., Dzama, K., Chimonyo, M., Raats, J. G., and Strydom, P. E. 2008. Meat quality of Nguni, Bonsmara and Aberdeen Angus steers raised on natural pasture in the Eastern Cape, South Africa. *Meat Sci,* 79(1): 20-28. doi: 10.1016/j.meatsci.2007.07.026

Muriuki, H. G. 2013. *Milk and Dairy Products, Post-harvest Losses and Food Safety in Sub-Saharan Africa and the Near East. A Review Of The Small Scale Dairy Sector – Kenya.* FAO Prevention of Food Losses Programme.

Ndung'u, P. W., Bebe, B. O., Ondiek, J. O., Butterbach-Bahl, K., Merbold, L., and Goopy, J. P. 2019. Improved region-specific emission factors for enteric methane emissions from cattle in smallholder mixed crop: livestock systems of Nandi County, Kenya. *Animal Production Science,* 59, 1136-1146. doi: 10.1071/AN17809

Nkonya, E., Johnson, T., Kwon, H. Y. and Kato, E. 2016. *Economics of Land Degradation in Sub-Saharan Africa*. In E. Nkonya, A. Mirzabaev & J. von Braun (Eds.), *Economics of Land Degradation and Improvement – A Global Assessment for Sustainable Development* (pp. 215-259). Cham: Springer International Publishing.

Nollet, L. M. L. and Toldra, F. 2011. *Handbook of Analysis of Edible Animal By-Products*. 6000 Broken Sound Parkway NW,Suite 300, Boca Raton, FL 33487-2742: CRC Press Taylor & Francis Group.

O'Brien, D., Capper, J. L., Garnsworthy, P. C., Grainger, C., and Shalloo, L. 2014. A case study of the carbon footprint of milk from high-performing confinement and grass-based dairy farms. *Journal of Dairy Science,* 97: 1835-1851. doi: 10.3168/jds.2013-7174

O'Brien, D., Hennessy, T., Moran, B. and Shalloo, L. 2015. Relating the carbon footprint of milk from Irish dairy farms to economic performance. *Journal of Dairy Science,* 98(10): 7394-7407. doi: 10.3168/jds.2014-9222

Opio, C., Gerber, P., Mottet, A., Falcucci, A., Tempio, G., MacLeod, M., . . . Steinfeld, H. 2013. *Greenhouse gas emissions from ruminant supply chains - A global life cycle assessment.* Food and Agriculture Organization of the United Nations (FAO), Rome.

Steinfeld, H., P. Gerber, T. Wassenaar, V. Castel, M. Rosales, and Haan, d. C. 2006. *The Livestock Long Shadow- Environmental Issues and Options*. Rome, Italy, Food and Agriculture Organization of the United States.

Thornton, P. K. 2010. Livestock production: recent trends, future prospects. *Philosophical Transactions of Royal Society B,* 365: 2853–2867. doi: 10.1098/rstb.2010.0134

Weiler, V., Udo, H. M. J., Viet, T., Crane. T.A., and De Boer, I. J. M. 2014. Handling multi-functionality of livestock in a life cycle assessment: the case of smallholder dairying in Kenya. *Current Opinion in Environmental Sustainability,* 8: 29-38. doi: 10.1016/j.cosust.2014.07.009