Life Cycle Assessment of buffalo milk: a case study of three farms in southern Italy

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# Abstract

The growing concerns about the relation of livestock activities and sustainability has led to technological progress and the adoption of best practices for reducing their impacts on the environment, including carbon emissions. In southern Italy, farming Mediterranean buffalos for milk production represents a significant portion of the economy. In this study we evaluate the environmental impacts of buffalo milk production using the Life Cycle Assessment approach. The analysis uses a cradle-to-gate system boundaries, an attributional approach and a Functional Unit equal to kg of Energy Corrected buffalo Milk (ECM). We use primary data collected from three farms in Southern Italy, covering a wide range of conditions including organic farming. We investigate the role of allocation method on the overall results and the role of buffalo milk productivity on the environmental impact estimates of milk production. Our results indicate that the environmental impacts of milk production are highly dependent on the chosen allocation method. The life cycle greenhouse gases emission ranges from 1.5 to 2.5 kgCO2eq per kg of ECM, which are slightly larger compared to those of cow milk; this is mainly due to higher milk productivity of cows compared to buffalos. The hot-spot analysis shows that the largest source of climate change impacts are direct emissions from enteric fermentation. The comparative analysis shows that no farm outperforms the other across the entire spectrum of categories and that the milk productivity of buffalos is a key aspect determining the environmental performance of each farm.

Keywords: Mediterranean buffalo milk production; life cycle assessment; greenhouse gases, organic production, allocation methods

# INTRODUCTION

In Italy, the agrifood sector represents 15% of the gross domestic product (GDP), with livestock being the main contributor (11.9%) to total revenues. In Southern Italy, a notable portion of the economy is represented by Mediterranean buffalos which are mainly bred for the production of Mozzarella di Bufala Campana DOP. In Italy, the value chain of buffalo breeding was about 600 million euros in 2019, with an indirect income of 2 billion of euros and more than 11 thousand of employees. However, direct and indirect activities linked to buffalo breeding are cause to different environmental problems, including climate change, biodiversity, marine pollution, acidification and water scarcity (Steinfeld et al., 2006).

Agriculture uses approximately 70 percent of the available freshwater supply, and roughly 30 percent of global agricultural water goes on livestock production (Ran et al., 2016), although several authors report a constant improvement of the water footprint in this sector (Mekonnen et al., 2019). But livestock’s direct and indirect freshwater consumption is only one of water-related challenges facing animal production: another is waste management and disposal (FAO, 2018). Runoff and nutrient leaks from concentrated sources of livestock waste are a hazard to freshwater sources, ocean and marine environments (Mekonnen and Hoekstra, 2012). Furthermore, ongoing research is focused on issues related to livestock farming such as the large use of antibiotics, the disposal of animal waste containing active solids and effects of veterinary antibiotics in plants (Tasho and Cho, 2016).

Emissions from livestock supply chains account for 14.5% of total anthropogenic greenhouse gases (GHG) emissions, with an annual value of 8 gigatons of CO2 equivalent in 2018 (Macleod et al., 2018). In turn, climate change affects animal farming directly (e.g. through heat stress and increased morbidity and mortality) and indirectly (e.g. through quality and availability of feed and forages, and animal diseases). For example, Jadhav, 2015 reports that anomalus heatwave in 2015 killed around 17 million birds in India, while Crescio et al., 2010 states that high temperature and air moisture could increase the cattle mortality of about 60%. On the other hand, Thornton and Herrero, 2014 summarizes the impacts of climate changes on crops quality and yield. The European Union (EU) aims to reduce carbon emissions from the agricultural sector by 33% in 2030 compared to 2005[[1]](#footnote-1). In addition, the EU National Emission Ceilings Directive, which set the maximum level of several pollutant in the atmosphere, establishes a reduction of ammonia and particulate matter emissions of 16% and 40% by 2030 compared to emissions recorded in 1990[[2]](#footnote-2).

The growing concern about the relation of livestock activities and sustainability has led to technological progress and the adoption of best practices for reducing GHG emissions. In Italy, the national GHG emissions report for the agriculture sector (Cóndor et al., 2008) outlines a progressive reduction of GHG emissions from 1990 to 2009: methane from enteric fermentation and from manure management reduced by 11% and 16%, respectively, whilst nitrous oxide from manure management and from soil emissions by 4% and 20%.

The use of Life Cycle Assessment (LCA) methodology in livestock management and food products has been increasing over the last years. Numerous Authors investigated the environmental impacts of livestock-derived products. de Vries and de Boer, 2010 compared the life-cycle environmental impacts of 25 peer-reviewed studies on the production of pork, chicken, beef, milk, and eggs. González-García et al., 2013 assessed the environmental impacts of mature cheese production in Portugal whilst Fantin et al., 2012 investigated the production of drinking milk; notably, they found that the farm phase is the main contributor to climate change, acidification and eutrophication impact categories. Thomassen et al., 2008 compared conventional and organic cow milks. Cecchini et al., 2016 investigated the environmental and economic sustainability of five dairy farms in the Umbria region, in Italy. Their study shows an average operating income of 0.03 €/L of milk and carbon footprint values ranging from 0.90 and 1.76 kg CO2 eq./L. Recently, Baldini et al., 2017 reviewed around 44 LCA studies on milk production published after 2009. The Authors concluded that future studies should investigate a broader range of impact categories, including biodiversity and water consumption; improve transparency, giving a detailed description of system boundaries and reporting the method used for impact calculation; and systematically conduct a sensitivity analysis for a better understanding the effect of the assumption made.

Despite the economic relevance of buffalo farming in Italy, few LCA studies investigated the environmental impacts of buffalo farms. Pirlo et al., 2014a estimated an average carbon footprint for 1 kg of Fat-Protein Corrected Milk (FPCM) in about 3.75 kg CO2eq. considering six Italian Mediterranean Buffalo milk farms. They found that the main sources of GHG emissions include animal enteric fermentation (45%) and indirect emissions from animal feed production (34%). The same Authors also analysed the impacts of buffalo milk production on abiotic depletion, photochemical ozone formation, acidification, and eutrophication (Pirlo et al., 2014a). The results suggest that increasing milk productivity is the most effective strategy to reduce climate change and photochemical ozone formation impacts, whilst enhancing the efficiency of feed utilization is crucial to mitigate abiotic depletion, photochemical ozone formation, acidification and eutrophication. Sabia and colleagues used LCA to assess the environmental impact of different livestock production systems (Sabia et al., 2018b) and to study two different heifer rearing systems: free-ranging and confinement (Sabia et al., 2018a). They concluded that the strategies to mitigate the effects on the environment impact also need to consider buffalo calves since their birth and different farming strategies (e.g., farming on natural pasture). More recently, Reddy et al., 2019 studied the production and environmental effects of two different feeding regimens, one based on traditional cottonseed meal (CSM) and other with coated urea (slow release urea - SRU) as a replacement for CSM on dairy buffalo production. They found that the CSM replacements with SRU could achieve an economical and eco-friendly production system from animal nutrition perspective.

The above demonstrates that a limited number of LCA studies focused on buffalo milk production. Notably, only two articles analysed impact categories other than climate change (i.e. acidification, photochemical ozone depletion, acidification and eutrophication) but, to our knowledge, no studies evaluated a broad range of categories. Furthermore, no literature study covered organic buffalo milk. This study aims to fill this gap. We evaluate the environmental performance of buffalo milk across a wide range of environmental categories, using primary data collected from three farms in Southern Italy. We also compare the performance of conventional and organic production methods. Finally, we investigate the effect of alternative allocation approaches on the LCA results.

# Methods

## Goal definition

The goal of this study is to evaluate the environmental impacts of buffalo milk production, using data collected from three farms in southern Italy (A, B and C). The LCA methodology is used for quantifying the environmental impacts, using an attributional approach and a cradle-to-gate perspective. A comparative and hot-spot analyses is performed to identify key factors affecting the environmental performance, with an emphasis on carbon emissions which are particularly critical for the dairy sector (Section 1). The effects of allocation procedures also is assessed as well as the role of buffalo milk productivity on the environmental impact estimates of milk production.

## Functional unit

The functional unit is expressed in terms of Energy Corrected Milk (ECM), The ECM represents an amount of milk with standardised percentages of fat and protein, which are equal to 4.0% and 3.3%, respectively. The conversion to ECM is performed via Eq. 1, where L, X and Z represent the amount of milk (in kg), and its fat and protein content (%) according to Campanile et al., 2003 :

|  |  |
| --- | --- |
|  | Eq. 1 |

The functional unit corresponds to 1 kg of ECM. It must be noted that the ECM formula adopted is slightly different from that in e.g. Baldini et al., 2017 or Pirlo et al., 2014b (which include FPCM as well as different versions of ECM). However, all these approaches yield very similar results that only differ by the second decimal digits.

## System Boundaries

The system boundaries of the LCA study are schematically depicted in Figure 1. For data collection purposes, a distinction between foreground and background systems is made (Clift et al., 2000). The foreground system comprises six sub-systems: i) in-house production of crops, covering cultivation, harvesting and refining; ii) purchase of additional feeds; iii) buffalo breeding, which includes water consumption, emissions from enteric fermentation as well as production of meat from surplus calves and buffalos cull; iv) production of milk, including the washing of equipment; v) management of manure, which comprises emissions from manure storage and, where relevant, electricity generation from anaerobic digestion; vi) utilities, which covers farm-wide consumption of electricity and fuels, and the end-of-life of lubricating oil. Farm B and, only in part, Farm C valorise manure via anaerobic digestion into electricity. Farm A and Farm C (for the other part) use manure as natural fertilizer, in place of artificial alternatives. Farm C is the only organic farm amongst those investigated.

This study does not include construction of the farms’ facilities (e.g. equipment, buildings and other capital goods), business travel and personnel commute from and to work, research and development activities, disposal of packaging of seeds and chemicals, and disposal of waste water used for the washing of premises.

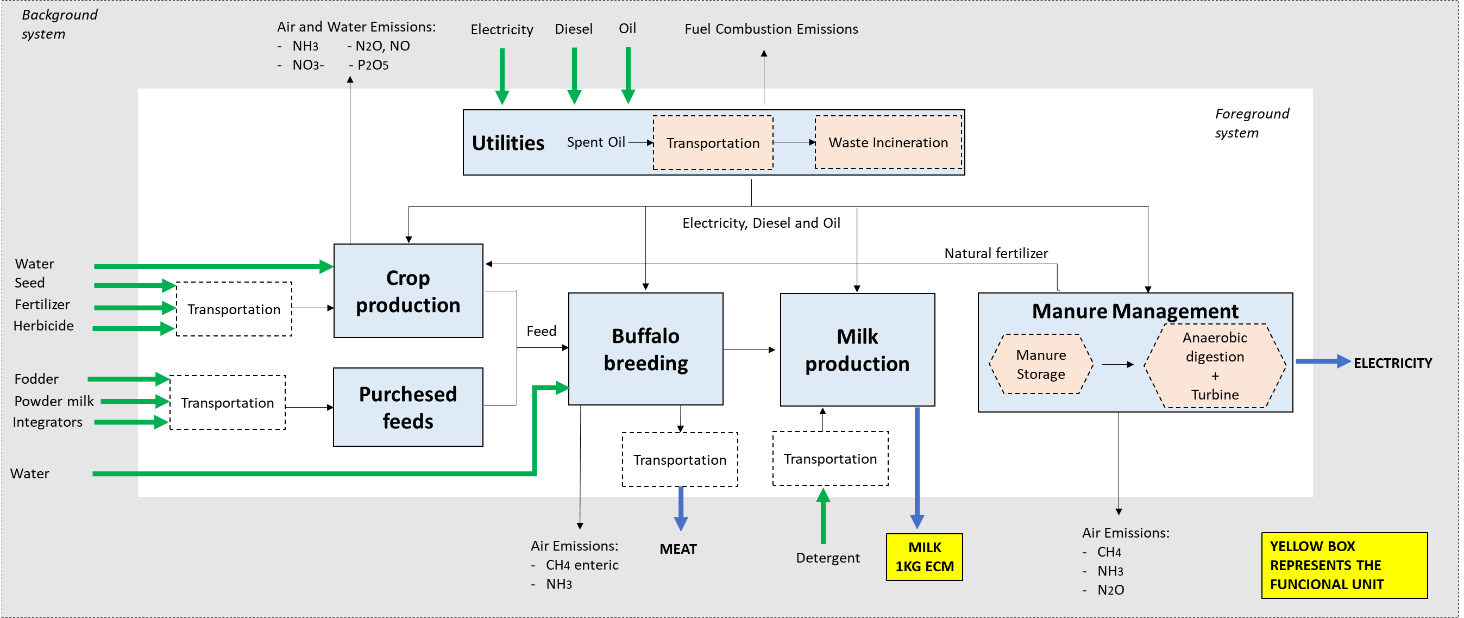


Figure 1 – Schematic system boundaries of buffalo milk production.

## Life Cycle Inventory

The foreground system is modelled using data collected for the year 2019 via a structured questionnaire that was distributed to the farmers. This is complemented with literature models to estimate emissions from enteric fermentation, manure management and fertilizer application. Data for the background system is based on commercial databases, including EcoInvent (cutoff, v3.6) [[3]](#footnote-3) and Gabi professional (2020)[[4]](#footnote-4). Table 1 reports key inventory data for the three farms investigated, whilst additional data is reported in Table S1 and S2 in the Supporting Information.

Dairy buffalo farms may differ for several aspects; these include the size and average milk yield of the herd, the amount of arable crops for internal forage production, the type of feeds and the strategy for manure management. Most aspects – including for example the number of animals in production or that of heifers and calves - vary with time. As shown in Table 1, the farms investigated in this study cover varying sizes of the herd, milk productivity and meat output, cultivated areas for crops production and fertiliser application. Notably, the average buffalo milk yield of Farm A and Farm C are similar to the Italian average according to Italian Association of buffalo farmer (ANASB), whilst that of Farm B is significantly higher[[5]](#footnote-5). Similar data are also reported for milk productivity of buffalo in Campania Region (Costa et al., 2020).

For all farms, the internal feeding system is based on maize, Italian ryegrass and whole cereal silage (partially produced on-farm and partially purchased) and grass or alfalfa hay obtained from the surrounding agricultural areas. The cultivated area for each crop and farm is reported in Table 1, whilst the amount of crops that are produced and/or purchased is provided in Table S1. We collected data on crop cultivation, including mineral and organic fertilizer, herbicide, seeds and water consumption (Table S1). To model direct and indirect emissions from fertilizer application, we used the Product Category Rules (PCR) on Arable Crops developed within the International EPD System (Environmental Product Declaration) (“EPD. Product Category Rules According to ISO 14025 (PCR) - Arable crops,” 2013) (Table S2). Transportation distances for purchased feeds are reported in Table S3; we modelled transport as a generic truck Euro 4/5 with different payloads, varying from 1 to 32 tons according to data provided by the farms. In addition to crops, we also considered complex feeds (like “Casablanca mix Fiock” which is used as feed for lactating buffalo); their production was modelled using ingredient lists reported on product labels and expert judgment for estimating their composition (as flacked corn 60%, flaked barley 30% and flaked protein pea 10%).

We estimated emissions from enteric fermentation using the Tier 2 methodology developed by the Intergovernmental Panel on Climate Change (IPCC, 2006) and formulas proposed by Cóndor et al., 2008 (Table S2). We modelled the production of detergents used for washing milking equipment using the active ingredients reported on the products’ labels (Table S3). For Farm C and Farm B, we assumed that excess electricity (Table S1), which is generated via a micro-turbine burning bio-methane from anaerobic digestion of manure, is sold to the grid as a co-product. When manure is not sent to anaerobic digestion, it is stored for at least 3 months before spreading. Emissions from storage were estimated according to Cóndor et al., 2008 (Table S2). Finally, data for electricity, diesel and oil consumption were provided as overall figures representing all activities in the farm (Table 1), with the relevant life-cycle emissions obtained from the ecoinvent database. For spent oil from agricultural machines, we assumed incineration as end-of-life treatment; this was also modelled using the ecoinvent database.

Table 1 – Key inventory data for the three farms investigated.

|  |  |  |  |
| --- | --- | --- | --- |
|  | Farm A | Farm B | Farm C |
| HERD | 950 | 620 | 898 |
| Production | 365 | 206 | 390 |
| Dry buffalo | 100 | 94 | 140 |
| Bulls buffalo | 15 | 15 | 40 |
| Calves 0 -3 months | 36 | 30 | 25 |
| Calves 3 -6 months | 30 | 90 | 60 |
| Calves 6 -12 months | 78 | 62 | 81 |
| Heifers 26 months | 226 | 62 | 81 |
| Heifers 20 at the 1°birth | 112 | 62 | 81 |
|  |  |  |  |
| Daily Milk yield (kg/day)/head | 9.0 | 10.3 | 8.5 |
| Protein (%) | 4.4 | 4.5 | 4.5 |
| Fat (%) | 8.3 | 8.2 | 7.9 |
| ECM, kg/ head | 14.8 | 17.0 | 13.7 |
| Meat output, kg/year (LW) | 60,336 | 33,419 | 78,018 |
|  |  |  |  |
| cultivated area, ha | 140 | 44 | 208 |
| Maize, ha | 70 | 30 | 40 |
| Ryegrass, ha | 65 | 22 | 95 |
| Alfalfa, ha | - | 7 | 30 |
| Triticale, ha | - | 15 | - |
| Sorghum, ha | - | 3 | - |
| Autumn winter mixture, ha | 65 | - | 43 |
| Produced feed, kg/ year | 5.39E+06 | 3.43E+06 | 3.57E+06 |
| off-farm feed, kg/ year | 1.35E+06 | 8.58E+05 | 2.34E+06 |
| Fertilizer P-N-k, kg/year | - | 2,800 | - |
| Fertilizer P-N, kg/ year | - | - | 15,000 |
| N fertilizer mineral, kg/ year | - | 13,400 | 33,500 |
| N at the field | 36,200 | - | 39,463 |
| diesel, L/ year | 1.10E+05 | 6.00E+04 | 1.00E+05 |
| oil, L/ year | 1.28E+03 | 5.00E+02 | 8.56E+02 |
| electricity, kWh/ year | 1.05E+05 | 7.38E+04 | 3.52E+04 |
| Electricity surplus, kWh/ year | 2.25E+06 | 1.76E+06 | - |

## Allocation

Dairy buffalo milk farms represent multi-functional systems. Besides milk, they produce meat (from culled buffalo and surplus of calves) and may also generate electricity, depending on the manure management strategy. Multi-functional activities present a specific challenge in LCA when the environmental impacts need to be allocated between different products (Hauschild et al., 2017). Sub-division, the preferred strategy according to the ISO standards (ISO, 2006), is not practicable because milk and meat cannot be produced separately (“European Commission, 2019. Product Category Rules for raw milk. VERSION 2.11 2019-09-06,” 2019; International Dairy Federation, 2016).

The handling of co-products is one of the most debated and unresolved dispute of LCA studies on milk yield, because the allocation strategy strongly affect the results (Notarnicola et al., 2016). Baldini et al., 2017, which reviewed over 44 LCA studies on milk production published after 2009, found that the most commonly adopted allocation methods include biological (which considers the energy required by cows to produce 1 kg of milk and meat) and economic allocation. Pirlo et al., 2014b investigated the carbon footprint of buffalo farms producing milk and meat. They found a reduction of around 4% in the carbon footprint of buffalo milk production using an economic allocation.

This study investigates the effect of different allocation methods on the environmental impacts of milk production. To the best of the Authors’ knowledge, there are no previous works in the literature dealing with milk allocation when electricity is a co-product. Both bio-physical and economic allocation methods are considered and compared with a scenario where no allocation is adopted.

The biophysical allocation method, which was proposed by the International Dairy Federation (IDF, 2010) is obtained according to Eq. 2:

|  |  |
| --- | --- |
|  | Eq. 2 |

Where AF is the allocation factor for milk, and BMQ is the ratio of the mass of live weight of all animals sold (including bull calves and culled mature animals per year) and the mass of fat and protein corrected milk (ECM) sold per year. With respect to electricity production, we follow IDF recommendations (International Dairy Federation, 2016), which entail crediting the system with the avoided environmental impacts associated with the generation of electricity from the conventional technology. We assumed that the excess electricity from the anaerobic digestion plant displaces that generated according to the Italian grid mix.

The method of economic allocation partitions the environmental impacts according to the revenues associated with the co-products. We averaged annual selling prices for milk and meat from the three farms, which equal 1.33 €/L and 0.94 respectively. The resulting allocation factors are reported in Table 2.

Table 2 - Allocation factors.

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Farm A** | **Farm B** | **Farm C** |
| NO ALLOCATION |  |  |  |
| Milk | 100% | 100% | 100% |
| Meat Surplus | 0 | 0 | 0 |
| Electricity Surplus | 0 | 0 | 0 |
|  |  |  |  |
| BIO-PHYSICAL + CREDITING |  |  |  |
| Milk | 73% | 83% | 68% |
| Meat Surplus | 23% | 16% | 32% |
| Electricity Surplus Credits | System expansion | System expansion | - |
| ECONOMIC ALLOCATION |  |  |  |
| Milk | 93% | 89% | 94% |
| Meat Surplus | 4% | 3% | 6% |
| Electricity Surplus | 3% | 8% | - |

## Impact assessment

We use the Environmental Footprint (EF) 3.0 method to quantify environmental impacts (Fazio et al., 2018; JRC, 2018); we consider 14 impact categories, which are reported in Table 3. A description of these categories can be found in Hauschild et al., 2017.

Table 3 - Environmental impact categories analysed.

|  |  |
| --- | --- |
| **IMPACT CATEGORY** | **METRIC** |
| Acidification | Mole of H+ eq. |
| Cancer human health effects | CTUh |
| Climate change | kg CO2 eq. |
| Ecotoxicity freshwater | CTUe |
| Eutrophication freshwater | kg P eq. |
| Eutrophication marine | kg N eq. |
| Eutrophication terrestrial | Mole of N eq. |
| Land use | Pt |
| Non-cancer human health effects | CTUh |
| Ozone depletion | kg CFC-11 eq. |
| Photochemical ozone formation - human health | kg NMVOC eq. |
| Resource use, energy carriers | MJ |
| Resource use, mineral and metals | kg Sb eq. |
| Respiratory inorganics | Deaths |
| Water scarcity | m³ world equiv. |

# Results and discussion

## Allocation

Figure 2 shows the effects of two allocation methods – bio-physical allocation combined with crediting for electricity, and economic allocation (see Section 2.5) – on the environmental impacts of buffalo milk production for Farm B. The chart compares the two allocation methods with the case where no allocation is adopted, that is, all environmental impacts associated with the farm are attributed to milk production. The results for Farm A and Farm C are reported in Figure S1 and S2 in the Supporting Information.

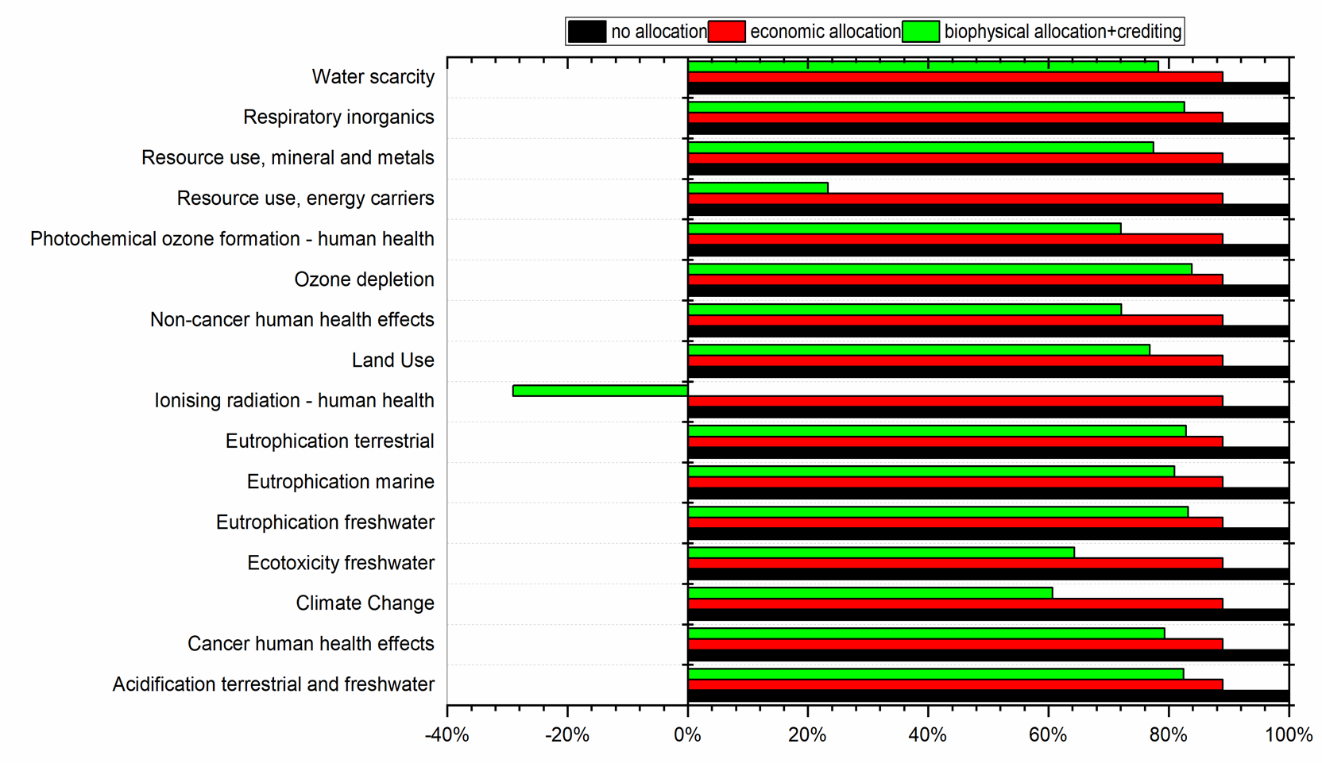


Figure 2 – Environmental impacts for milk production at farm B according to different allocation methods.

The chart shows that the economic allocation is significantly more conservative than the alternative method (bio-physical allocation plus crediting) because it entails a lower reduction from the no allocation scenario; in other words, it allocates a larger portion of the environmental impacts to milk production. For Farm B, economic allocation attributes 89% of the farm’s environmental impacts to milk for each environmental category (see Table 2). For most categories, the impacts allocated by the alternative method range from 60% to 82%. The categories ionising radiation and resource use, energy carriers represent a notable exception, with substantially lower allocation factors that equal -20% and 20%, respectively. Notably, a value of -20% indicates that the impact score in the category is negative, i.e. the environmental benefits from the avoided activities are larger than the impacts of milk production.

The economic allocation approach is representative of the revenues of the farm relative to the two co-products. The resulting allocation factors implies that nearly 90% of the revenues of dairy buffalo farms derive from the sale of milk, with the remainder being shared between meat surplus and electricity (see Table 2). The bio-physical allocation plus crediting approach partitions the environmental impacts between milk and meat based on the proportion of feed used for lactation and growth of the herd whilst subtracting the avoided environmental impacts of electricity generation. This method attributes a smaller proportion of the environmental impacts to milk for two reasons. First, the portion of feed used for lactation is lower than that of revenues associated with milk (83% compared to 89%, as shown in Table 2). Second, the avoided burdens of electricity production yield an additional significant reduction in the environmental impacts, in particular in those categories where the credits from electricity are particularly relevant, i.e. ionising radiations, climate change, ecotoxicity and resource use - energy carriers (see hot-spot analysis in Section 3.4).

The results for the other farms (Figure S1 and S2) confirm that economic allocation is more conservative than bio-physical allocation plus crediting approach, allocating around 93% and 94% of the impacts to milk for Farm A and Farm C, respectively. The allocation factors for these farms are higher compared to Farm B, due to smaller amounts of meat sold. The alternative allocation method yields a smaller range of variation for the environmental impacts of Farm C (from 45% to 76%) compared to Farm B, because the farm generates less electricity surplus. Farm A does not generate any electricity from manure management; therefore, the environmental impacts allocated to milk production are apportioned only on the basis of the bio-physical allocation factor, which is equal to 68% for all categories (Table 2).

This analysis is in line with literature findings in suggesting that the environmental impacts of buffalo milk production are highly dependent on the chosen allocation method. The economic allocation, which is the most widely adopted method in literature on milk production (Baldini et al., 2017) (Section 2.5), is based on precept that revenue generation is the primary reason for any economic activity, and therefore that the activity generating the largest share of revenues is to be attributed the largest portion of the environmental impacts. The main limitation is that the prices of many co-products, especially of milk, meat and electricity, vary temporally and spatially (they differ between countries, but may also vary within the same country). This entails that the results from different LCA studies may not be immediately comparable and that key differences in environmental performance of competing farms may be concealed by variations in the allocation factors.

The bio-physical approach, which is preferred according to the ISO hierarchy (ISO, 2006) and recommended by the International Dairy Federation (IDF, 2010), is based on an underlying physical causality between feed for growth and lactation, and environmental impacts. The crediting approach is mathematically related to the system expansion method, and therefore, according to the ISO hierarchy, preferred to economic allocation. However, it must be noted that the crediting approach suffers from similar limitations to economic allocation: the identification of the avoided environmental activities is mostly subjective, which hinders comparability of results; and even when literature approaches for selecting the counterfactual scenarios are adopted (Weidema et al., 1999), these change both spatially and temporally.

The above demonstrates the importance of developing a standardised approach to enable comparison between LCA studies that allocate impacts between co-products. This is outside the scope of this article, but it should be part of future efforts in the methodological development of LCA. In the remainder of this article, we focus on the results obtained via bio-physical allocation for meat surplus and crediting for electricity surplus, in accordance with the IDF recommendations; the results for the economic allocation method are reported for completeness in the Supporting Information.

## Climate change impacts

Figure 3 reports climate change results for the three farms investigated, using the bio-physical allocation plus crediting approach. The chart also reports literature estimates for buffalo milk production in the Umbria Region in Italy (Cecchini et al., 2016), in the Mediterranean area (Pirlo et al., 2014b) and for different heifer rearing systems (Sabia et al., 2018a) as well as cow milk (Baldini et al., 2017). The latter reviewed around 44 LCA studies on milk production published after 2009. The literature estimates are reported as box and whisker plots with horizontal lines, boxes and whiskers representing, respectively, median values, 25th and 75th, 1st and 99th percentiles. The numerical values as well as results for economic allocation are reported in Table S3. Although we use a Functional Unit that takes into account different compositions of milk, the comparison between cow and buffalo milk must be made with caution because the products may not be recognised as being fully replaceable each other. For example, buffalo milk may provide an alternative to those allergic to cow milk. In addition, the proteins in buffalo milk have been recognised to offer additional health benefits, i.e., antimicrobial, immunomodulation, antitumor, antidiabetic, antihypertensive and antioxidant properties(Basilicata et al., 2018)*.*



Figure 3 – Climate change results for the three farms investigated in this study, compared to literature estimates for cow and buffalo milk.

The results show that, at 1.5 kg CO2-eq., Farm B features the lowest carbon footprint among the farms investigated, compared to 2.3 and 2.5 kg CO2-eq. for Farm A and Farm C, respectively. The carbon performance of Farm B is mainly due to higher milk productivity and higher electricity surplus (and thus avoided environmental impacts) compared to the other two farms (see Table 1). The other allocation approaches reported in Section 3.1 generate similar results(see Table S4 of supplementary Material), suggesting that Farm B generates the smallest carbon emissions independently of the allocation approach used.

The comparison with literature data shows that our results are comparable with, but in the lower range (1-25th percentile) of the literature estimates for buffalo milk. The chart also indicates that the carbon emissions associated with cow milk production are substantially lower than those reported for buffalo milk, varying from 0.58 to 1.68 kg CO2-eq. This is mainly due to the fact that cows yield higher milk productivity than buffaloes (34.05 vs. 8.78 kg/day on average in Italian Holstein and Mediterranean buffalo, respectively[[6]](#footnote-6)). We note that the carbon footprint of Farm B is included in the upper quartile for cow milk. When other allocation approaches are used, the farms’ carbon emissions are higher (from 32 to 540%) than that of cow milk.

The comparison with the literature must be done with caution, for two reasons. First, as noted in Section 3.1, LCA results on milk production are significantly dependent on the allocation method; and we could not discern which results were obtained for a specific allocation method. Second, climate change results are also dependent on global warming potential (GWP) factors, which are updated approximately every seven years by the Intergovernmental Panel Climate Change. Older studies may underestimate climate change impacts because the GWP of relevant greenhouse gases have been repeatedly revised upwards as new scientific evidence on climate change was developed; for example, the GWP for methane increased from 21 to 28 kg CO2-eq./kg CH4 from the third (IPCC, 1995) to the fifth assessment reports of the IPCC (IPCC, 2014).

Figure 4 examines in detail the sources of climate change impacts. The chart reports hot-spot analysis for Farm B in the form of Sankey diagram; those for Farm A and Farm C are reported in Figure S3 and S4. Carbon emissions from enteric fermentation contribute to nearly half (45%) of overall climate change impacts; other significant contributors include machine operation (i.e. production, transportation and consumption of fuels - 19%), purchased feeds (13%) and fugitive emissions from the bio-digester (11%). The remaining sources of climate impacts have combined contributions of around 10%, with each contributing to less than 2.5%. Enteric fermentation, machine operation and bio-digester are the most significant sources of direct (i.e., on-site) emissions, which represent over 80% of total. On the other hand, purchased feed is the main contributor to indirect emissions. Methane emissions generate around 60% of climate change impacts, followed by CO2, at 31% and N2O at 8%. Methane emissions mainly originate from enteric fermentation and from fugitive emissions from bio-digester, whilst CO2 is released by machine operation and from the production and transportation of purchased feed. The latter is also responsible for the majority of N2O emissions (the other key contributor being the production and application of fertilizers).



Figure 4 – Sankey diagram of the greenhouse gas emissions and credits for Farm B. PFC: perfluorocarbons.

The Sankey diagrams for Farm A and Farm C (Figure S3 and S4) provide similar results, with some notable differences. The share of direct emissions from Farm A is lower (73%), because there are no fugitive emissions from the bio-digester: the farm uses manure as natural fertilizer instead for generating electricity. It must be noted that the Sankey diagrams do not include the environmental benefits – i.e. the credits - of generating electricity. The absence of a bio-digester plant also entails that the contribution of methane emissions is smaller, at ~ 51%.

Even though enteric fermentation is a natural process that is inherent of the digestive physiology of ruminants, several strategies to reduce carbon emissions are available; these are mainly related to the type and quality of the animals’ diet. The release of methane from enteric fermentation is mainly due to the degradation of structural carbohydrates (fiber) by some population of bacteria present in the rumen (Asselstine et al., 2021). Therefore, methane production decreases when i) daily animal ingestion increase, ii) the percentage of fiber and fodder decreases and iii) the percentage of non-structural carbohydrates (such as starch) increases. Additional strategies include specific treatments for increasing the starch degradability, adoption of more degradable fodder or grinded fiber, the addition of unsaturated fats (González et al., 2018) other additives such as tannins or essential oils (Min et al., 2020). A correct forage/concentrate ratio is also an effective means to reduce CH4 emissions (Lovett et al., 2003).

The carbon emissions from machine operation, which includes production and transportation of fuel as well as direct emissions from its consumption, are strictly dependent on the type of machines and their efficiency. In this study, we estimated direct emissions using datasets for tractors from ecoinvent with validity expiring in 2012; notably, this is consistent with the average age of the machines used in the farms investigated. Replacing old with new (and thus more efficient) machines is likely to yield a reduction of carbon emissions. Furthermore, this may also allow to improve the forage and feedstuff yields/hectare, which in turn can give other advantages, such as reduction of purchased feed and relative transportation.

## Hot-spot analysis

Figure 5 reports contributions of each sub-system (see Figure 1) to environmental impacts of Farm B, including all environmental categories except climate change (discussed in Section 3.2). The charts for the other farms are reported in Figure S5 and S6. Numerical values are included in Table S5.



Figure 5 – Hot-spot analysis for Farm B.

The chart shows that the majority of the environmental impacts originate from purchased feeds (mainly fodder) and utilities (machine operation), with combined contributions varying from 13% for the acidification category, up to 98% as for cancer and non-cancer human health effects, and land use. Buffalo breeding, which includes enteric methane emissions and ammonia emissions from animal excrete, is only relevant to acidification, terrestrial eutrophication and respiratory inorganics (48, 47 and 30% respectively); whilst in-house production of crops has non-negligible contributions in several categories including water scarcity, eutrophication, acidification and respiratory inorganics. The contributions of manure management and milk production are minor to negligible. The credits due to electricity generation from the bio-digester are particularly (>40%) relevant in the categories ionising radiation and resource use (energy carriers); notably, for the former the credits are higher than the sum of all other impacts, implying a net saving.

The hot-spot analysis for Farm A (Figure S5) identifies similar sources of environmental impacts, with key differences including higher contributions of manure management to terrestrial eutrophication, acidification and respiratory inorganics, and the absence of credits from electricity generation. These differences are linked to the manure management strategy that entails using manure as natural fertilizer. This leads to reduced consumption of artificial fertilizer but also higher fugitive emissions of ammonia from storage of manure before its spreading.

The results for Farm C (Figure S6) highlight substantially higher contributions from crop production, particularly in terms of water consumption and land use. These are related to the fact that this farm employs an organic method of farming, which typically entails lower crop productivity (due to the inability to use non-natural fertilizer). Furthermore, the credits from electricity generation are less significant, because the manure produced is only partially used for energy valorisation, with the remainder being used as fertilizer.

## Comparative analysis and the role of buffalo productivity

Figure 6 compares the life-cycle performance of the three farms investigated across the full spectrum of environmental categories; the underlying numerical values are included in Table S6. The impacts are normalized using reference values for per-capita impact in the European Union (Sala et al., 2018). Notably, we report in darker colours the environmental impacts when the farms are assumed to attain the same average productivity, which we arbitrarily set to be equal to that of Farm B (10.3 kg of milk per head per day).

The comparative analysis shows that no farm outperforms the others across all environmental categories. Farm A yields the largest impacts in the vast majority of categories, with the exception of land use, water scarcity and non-cancer human health. Farm C generates the largest impacts in these categories, but also the smallest in cancer human health and ecotoxicity freshwater. Farm B outperforms the other farms in the remaining categories.

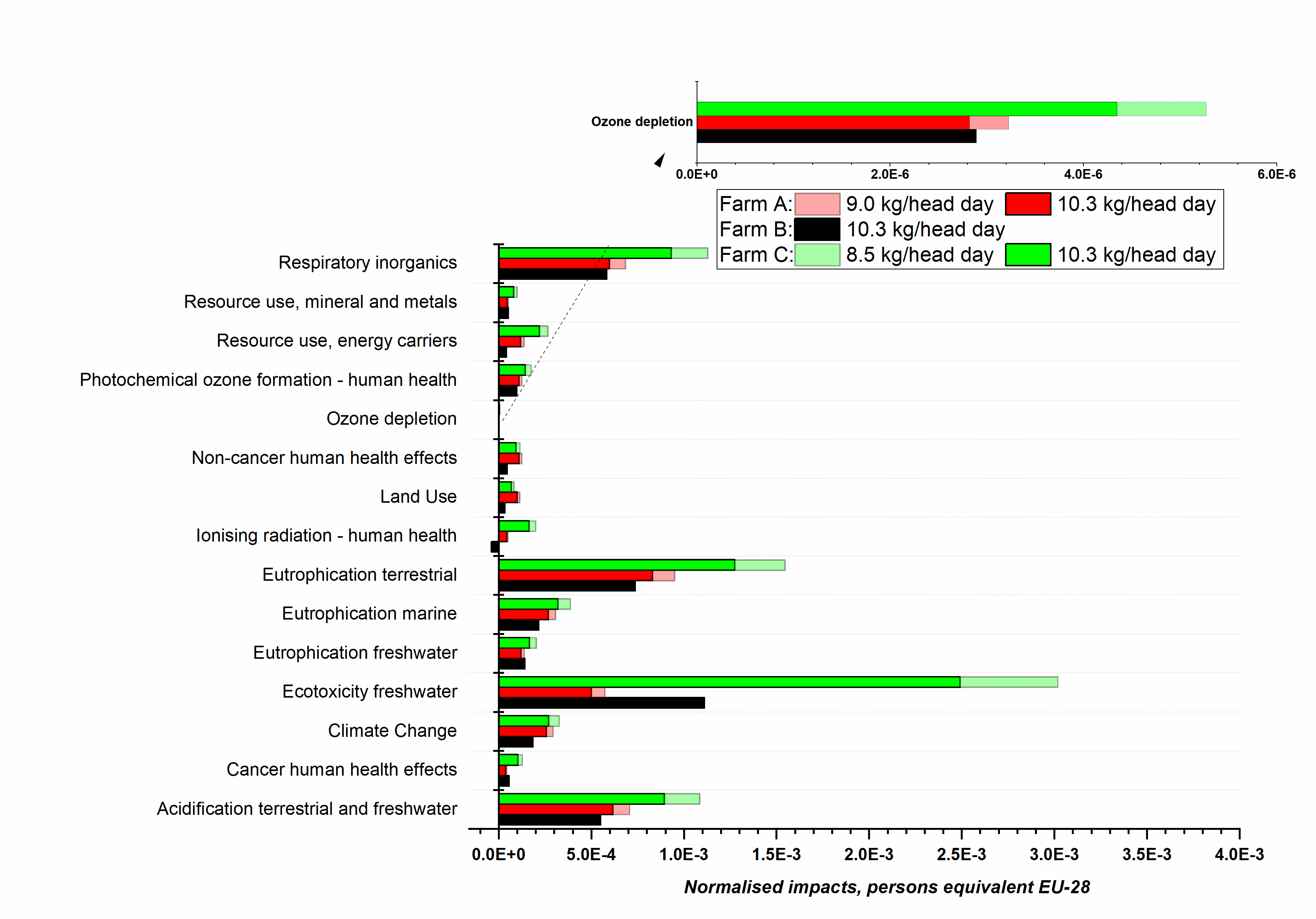


Figure 6 – Comparison of environmental impacts of milk production for the three farms investigated. Light-coloured bars represent impacts considering varying productivity of animals. Dark-coloured bars assume all farms have same productivity, equal to that of Farm B (10.3 kg/head day)

The farms’ relative environmental performance is determined by a combination of multiple factors, including buffalos’ milk yield, the manure management strategy, the type of animal feed and the proportion that is cultivated/purchased. Milk productivity is arguably one of the most influential parameters: higher productivity entails lower environmental impacts per unit of milk because the overall, farm-wide impacts are distributed across larger amounts of milk. This parameter is affected by several aspects that are related to the farm management, such as buffalo diets and health, and region of growth; but crucially, it also depends on the genetics of the animals, which is not related to the farm operation.

For this reason, we adjusted the comparison considering all farms have the same milk productivity; in essence, this entails reducing the environmental impacts of Farm A and Farm C in proportion to the difference in productivity compared to Farm B. The productivity-adjusted comparison shows that Farm A and Farm C yield lower environmental impacts, approaching the performance of Farm B. Interestingly, adjusting for productivity only changes the difference between the impacts of the farms in each category, but not the ranking.

The remaining differences in the environmental performances of the farms are explained by the other above-mentioned aspects: manure management strategy and type of animal feed. The former primarily affects the categories ionising radiation, resource use (energy carries), terrestrial eutrophication and acidification (as discussed in Section 3.3), with the latter explaining the remaining differences. For example, the significant water consumption of Farm A compared to the other farms is due to higher proportion of in-house cultivated corn, which is a water-intensive crop.

The results are also interesting in terms of comparison between conventional (Farm B and Farm C) and organic farming (Farm A). Farm A has larger environmental impacts than the conventional counterparts in terms of land use, water scarcity and non-cancer human health, regardless of whether impacts are adjusted for productivity or even if credits for electricity production are considered. Higher impacts in the categories land use and water scarcity primarily stem from in-farm production of crops, which have lower yields due to inability of using non-natural fertilizers. Higher land use is also directly related to larger breeding space that is required in organic farming. Finally, higher non-cancer human health impacts originate from production of purchased feed, for similar reasons to those mentioned for in-farm crops.

4. CONCLUSIONS

This article presented a comprehensive Life Cycle Assessment (LCA) study that assessed the environmental impacts of buffalo milk production from three farms in southern Italy. It analysed different approaches for allocating the environmental impacts of the farms to milk production, and investigated the role of buffalos’ milk productivity on the environmental performance.

The analysis confirms other literature studies in demonstrating that the environmental impacts of milk production are highly dependent on the chosen allocation method. Economic allocation consistently apportions larger share of environmental impacts to milk production compared to the bio-physical plus crediting approach. However, both methods suffer from similar limitations regarding spatial and temporal variability of the allocation factors. Following recommendations from relevant Product Category Rules (PCR), we reported and discussed in the main text the results obtained via the bio-physical plus crediting approach.

The analysis of climate change impacts shows that i) the three farms investigated yield lower impacts compared to median values from literature, and that ii) buffalo milk typically has larger carbon footprint compared to cow milk; this is mainly because of higher milk productivity of cows compared to buffalos. The hot-spot analysis shows that the largest source of climate change impacts are direct emissions from enteric; these could be reduced via changes in the diets of the animals. Other significant contributors include direct emissions from machine operation, purchased feed and, where applicable, fugitive emissions from the bio-digester, which is used to generate electricity from manure. The other environmental categories are primarily dominated by impacts associated with purchased feed and machine operation, with credits from electricity generation being particularly significant in a limited number of categories, including ionising radiation and resource use (energy carriers). Possible strategies to improve the environmental impacts should therefore focus on the improvement of machine operations through precision agriculture techniques, which can lead to increased crop production and, consequently, reduced feedstuff purchase.

The comparative analysis demonstrated that no farm outperforms the other across the entire spectrum of categories. Farm A and Farm B yield respectively the largest and smallest impacts in the majority of categories. The milk productivity of buffalos, which varies from farm to farm, is a key aspect determining the environmental performance of each farm: Farm A and Farm B have respectively the lowest and highest productivity. The productivity-adjusted comparison shows smaller differences in the environmental performance of the farms, though the ranking in each category remains the same. The remaining differences are explained by a combination of type of feed (including the portion that is cultivated in-house and purchased) and the strategy for managing manure.

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