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Comparing productivity and feed-use efficiency between organic and conventional livestock animals

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**Abstract**

Livestock animals play a key role in organic farming systems by providing nutrients for croplands through manure production and nutrient-dense food for human consumption. However, we lack global, synthetic view about livestock productivity in organic farming and about its differences with conventional farming. Here we fill this important gap of knowledge by providing a first global comparison highlighting differences between organic and conventional farming on animal productivity, feeding strategy and feed use efficiency in dairy cattle, pigs and poultry (both layers and broilers). We found (a) a 12% lower animal productivity under organic treatment, (b) significant differences in feeding strategy, especially for organic dairy cattle fed with a lower proportion of concentrate and food-competing feed than in conventional systems, (c) an overall 14% lower feed-use efficiency under organic treatment (−11% and −47% for organic dairy cattle and poultry broilers, respectively) compensated by (d) a 46% lower human-food vs animal-feed competition in organic dairy cattle. These results provide critical information on the sustainability of organic livestock management. They are also key for modelling global organic farming expansion while avoiding overestimation of organic farming production in upscaling scenarios.

1. Introduction

Scaling up organic farming is often considered as a promising option for a more sustainable food system (Reganold and Wachter 2016). Global organic food sales were multiplied four-fold between 2001 and 2016, an increase driven by a strong consumer demand and constant policy support towards more sustainable forms of agriculture (Willer and Lemoud 2018). Nevertheless, the sustainability of organic farming remains debatable, in particular due to its lower productivity compared to conventional — i.e. non-organic — farming (Seufert and Ramankutty 2017, Reganold and Wachter 2016): on average, organic crops exhibit a 19%–25% yield gap compared to conventional farming (De Ponti *et al* 2012, Seufert *et al* 2012, Ponisio *et al* 2015). The effects of these crop yield gaps have been considered in organic farming upscaling scenarios in order to test the potential of that way of farming to meet global food security goals

(Erb *et al* 2016, Muller *et al* 2017) and high environmental benefits.

However, none of those scenarios have considered consistent differences between organic and conventional livestock farming (Erb *et al* 2016, Muller *et al* 2017, Barbieri *et al* 2019). This is likely due to the fact that, whereas some individual studies have compared the animal productivity and feed-use efficiency of organic and conventional farms (e.g. see Van Wagenberg *et al* 2017, Rös *et al* 2018), no effort has been conducted so far to synthesize this information at the global scale. Such an important gap of knowledge is surprising due to the utmost importance of livestock animals for both food security and organic farming sustainability. On the one hand, livestock production provides rich food commodities with a high concentration of amino acids and nutrients (Mottet *et al* 2017), contributes to replace synthetic fertilizers by animal manure (Watson *et al* 2006) and fulfils a number of ecosystem services

(especially when grass-fed). On the other hand, livestock production is a major anthropogenic driver of pollution and challenges food security through strong feed/food competition (Wilkinson 2011, Ertl et al 2015, Mottet et al 2017, Laisse et al 2018, Uwizeye et al 2020).

In this study, we aim to fill that important gap of knowledge by providing, synthesizing and comparing data on organic vs conventional livestock production levels and feed use. In particular, we assess whether organic livestock farming differs from conventional in terms of animal productivity, composition of feed ration and feed-use efficiency. Because livestock feeding may have major consequences on feed/food competition, we paid specific attention to the composition of animal feed rations in organic vs conventional farming systems and to feed use efficiency of animals fed on food-competing feeds. We hypothesized that organic livestock (a) are less productive and (b) have a lower feed use efficiency, but — due to differences in feeding strategies — (c) also have a lower use of food-competing feed than their conventional counterparts. Finally, we hypothesized that those results vary across animal functional types (mainly ruminants vs monogastrics).

2. Material and methods

2.1. Literature search and screening

The objective of our comparison was to evaluate whether organic and conventional farming systems differ in terms of livestock productivity, with a particular focus on feed-use efficiency and dietary composition. To do this, we searched for scientific papers comparing organic vs conventional livestock productions and providing data on productivity as well as on feed rations. We included both research papers based on farm monitoring and those on experimental data. We focused our analysis on five main animal species — cattle, pigs, poultry, goats and sheep — as well as on three production types — meat, egg and milk. In order to identify suitable publications, we screened the ‘Web of Knowledge’ and the ‘Scopus’ portals using the following complex Boolean search:

((Organic OR Biological OR Ecological OR Sustainable OR conventional) NEAR/0 (Farm* OR Agriculture OR Livestock OR Animal OR Husbandry OR system* OR management OR production OR dairy)) & ((Ruminant* OR monogastric*) OR (Beef OR Cattle OR Dairy OR Cow OR Heifer OR Calf OR Calves) OR Buffaloes OR Sheep OR Goat OR (Swine OR Pig) OR (Poultry OR Chicken OR Broiler OR Turkey OR Hen OR Duck OR Layer)) & (Feed OR ‘Life Cycle’).

The last search run was conducted on 10 September 2020, yielding 2085 articles. These articles were further screened via a selection process based on three main steps in order to limit the number of papers to those that fulfilled our selection criteria (figure S1 (available online at

stacks.iop.org/ERL/16/024012/mmedia)). After a first selection based on title and abstract screening (in order to exclude off-topic papers), we screened 201 articles to select those that (a) specifically mentioned one organic system (either certified or in line with the definition of organic agriculture given in the *Basic Standard for Organic Production and Processing* of the International Federation of the Organic Agricultural Movement (IFOAM)) and one non-organic system that we defined as conventional, (b) provided animal production and animal feed (either the entire feed ration or at least the share of concentrate feed) or the feed-use efficiency directly, (c) reported data from animal or farm observation (national statistics and results from models were excluded) and (d) had a number of observations (i.e. number of monitored animals) higher than 20. After this process, we retained 34 pertinent articles that referred to four livestock species and the three production types mentioned, covering 14 countries worldwide. Nevertheless, we only identified a limited number of papers that focused on beef cattle (three comparisons) and none on goats and sheep that fitted our selection criteria. Therefore, we finally excluded beef cattle from the analysis — i.e. we used only 37 comparisons from 31 papers to run our statistical analyses. Among the different livestock species, dairy cattle were the most highly represented (20 comparisons), followed by a much lower number of comparisons for pigs, broilers and layers (table 1). Ruminant-related data were mainly taken from farm monitoring (18 comparisons out of 20 for dairy cattle), while monogastric-related data were mainly experimental. Developed countries are the most highly represented (31 comparisons), while only six studies were located in developing countries (table 1). Studies selected were mainly located in Europe (25 comparisons) and the Middle-East (6 comparisons) (figure S2). The complete list of studies is reported in table S1.

We are aware of the reduced size of our dataset. This is mainly due to the fact that papers often report incomplete information, thereby not fulfilling our selection criteria. We tried to make up for this by directly contacting a number of authors in order to collect additional data, with a low share of response. Therefore, our dataset remained heterogeneous, meaning that we could not calculate all of the requested variables for each article, hence leading to fluctuation in dataset size among the considered variables. Despite such shortcomings, our comparison represents the first attempt to globally quantify and compare livestock production performances between organic and conventional production farming based on the best available literature.

2.2. Data extraction

In each selected paper, we extracted one or several pieces of information comparing one organic system and one conventional system in terms of animal

Table 1. Number of organic-to-conventional comparisons for each animal category, type of observation, country level of development and studied variable.

Total no. comparisons	Type of observation		Level of development		Animal productivity		Feed-use efficiency		
	Experiment	Farm monitoring	Developed countries	Developing countries	Total feed	Concentrate feed	Food-competing feed		
									Developed countries
Cattle dairy	20	2	18	19	1	19	18	19	6
Pig meat	7	7	0	5	2	7	6	6	6
Poultry egg	4	3	1	2	2	4	4	4	4
Poultry meat	6	5	1	3	3	6	6	6	4
All animals	37	17	20	29	8	36	34	35	20

productivity, feed ration and feed-use efficiency. We encountered cases where articles provided several different organic systems and/or several different non-organic systems. We therefore had to gather data in order to extract one or several comparisons. When one treatment for organic or non-organic treatments was compared to several of the other treatments, a mean was calculated with the other treatments in order to have only two treatments to compare. When several treatments of both organic and non-organic systems were present, treatments were combined (based on similar geographical position, breed or housing system) in order to make several comparisons.

We applied the following data extraction procedure: (a) when available, we recorded data reporting production quantities expressed as the amount of animal product per unit of time and per head. We considered the animal product to be the main product of the production type, i.e. animal by-products (e.g. meat from reformed dairy cattle) are not considered. Animal production quantities were expressed as energy corrected milk (Tyrrell and Reid 1965), kg of egg and kg of live weight gain. When not available, production was calculated to fit the previous units (see supplementary methods); (b) when available, feed ration composition was recorded as the amount of dry matter (DM) per unit of time and per head for each feed type. Data were sometimes in the form of fresh weight: we converted such data to DM equivalents using DM coefficients retrieved from the Feedipedia and Feedtables databases (see supplementary methods). When the detailed feed ration composition was not available, composition in terms of forage and concentrate was recorded; (c) we recorded feed-use efficiencies expressed as the ratio between production quantity and feed intake, although other authors express feed-use efficiency as the ratio between feed intake and production (Wilkinson 2011, Mottet *et al* 2017). Because both formulas represent a good feed-use efficiency indicator (Laisse *et al* 2018), we decided to use the former for easier interpretation and greater comparability with crop input use efficiency. If feed-use efficiency was not available, we calculated it using the data recorded in the two previous steps.

Different authors question whether calculating feed efficiency as the ratio of production to total feed ingested is an appropriate indicator. These same authors instead suggest calculating independent feed-use efficiency as the ratio between production and specific feed items, e.g. concentrate or food-competing feed (Wilkinson 2011, Ertl *et al* 2015, Mottet *et al* 2017). These two other feed-use efficiency indicators are important in order to understand the impact of livestock production on feed/food competition. We therefore also recorded feed-use efficiencies based on concentrate and food-competing feeds when available.

Feed-use efficiency is commonly calculated as a mass ratio (Mottet *et al* 2017) (equation (1)).

$$\begin{aligned} & \text{Feed use efficiency} \\ &= \text{kg of animal product/kg of ingested feed} \\ & \times (\text{expressed in dry matter}). \end{aligned} \quad (1)$$

Nevertheless, since energy and protein are two important nutritional human and animal components, feed-use efficiency is often calculated as the ratio between production expressed in energy and crude protein (CP) and the energy or protein ingested as feed (Wilkinson 2011, Ertl *et al* 2015, Mottet *et al* 2017, Brito and Silva 2020). Similarly, we recorded the energy and CP feed-use efficiency for all feed categories when available (equations (2) and (3)).

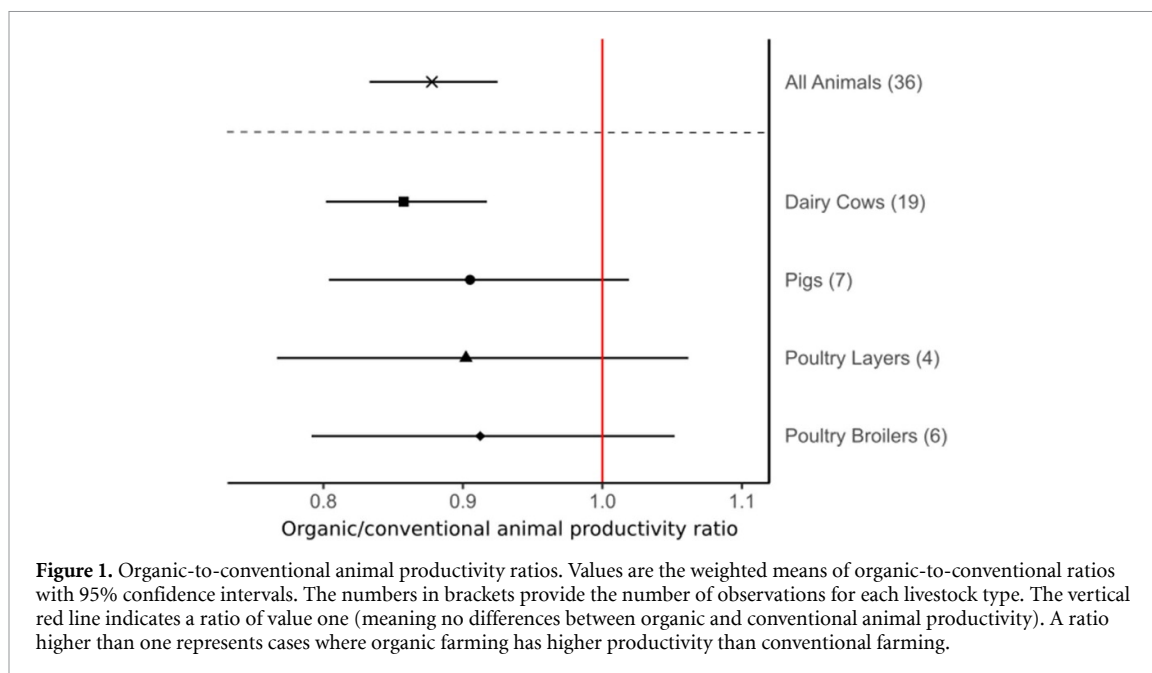
$$\begin{aligned} & \text{Energy feed use efficiency} \\ &= \text{MJ in animal product/MJ in feed} \end{aligned} \quad (2)$$

$$\begin{aligned} & \text{Crude protein feed use efficiency} \\ &= \text{kg CP in animal product/kg CP in feed.} \end{aligned} \quad (3)$$

In addition to those efficiency indicators, we recorded the net feed-use efficiency defined as the ratio of the energy (or protein) available for human consumption in the animal product to the energy (or protein) available for human consumption in the feed ration. Although several authors suggested different calculation methods for this indicator, we used the method developed by Laisse *et al* (2018) because it is the only one that provides a detailed classification of feed products with their corresponding human-edible energy and protein content. Since no proof of differences in energy and protein content between organically-produced and conventionally-produced food is clearly available (Srednicka-Tober *et al* 2016), we used the same coefficients to estimate animal food product energy and protein content (following Laisse *et al* 2018).

2.3. Statistical analysis

In our comparison, we used the non-organic treatment as the control. To estimate productivity and feed use efficiency differences between organic and conventional systems, we calculated as an effect size the organic-to-conventional log response-ratios (Makowski *et al* 2017) for both productivity and feed-use efficiency. We then tested whether the mean effect size was significantly different from zero using a linear weighted mixed-effect model. The production type (e.g. dairy cows, poultry broilers) was set as a fixed factor, whereas we used a dummy variable representing each paper ID number as a random factor. The absence or the poorly reporting of variance values in the selected papers did not allow to follow



the common study-weighting procedure — meaning weighting each study by the inverse of its variance. However, alternative procedures are possible for example by weighting each study by its number of observations (i.e. the number of monitored animals in our case) (Letourneau *et al* 2011, Philibert *et al* 2012, Beillouin *et al* 2019). In addition, we compared the results obtained following this statistical procedure with results based on simpler statistics using non-weighted means. Note that this last approach does not account for the often greater accuracy of studies that report data from large number of monitored animals.

Since livestock management differs across animal species and production types and since organic practices may vary depending on the geographical location, we disaggregated our dataset according to the different (a) livestock species, (b) production types (meat, milk or eggs) and — for each of them — (c) type of data (experimental vs on-farm observations) and (d) geographical locations (developed vs developing regions). We then run our statistical analyses for each sub-group. Note that the developed vs developing country grouping is common when comparing organic to conventional farming (Seufert *et al* 2012, Barbieri *et al* 2017). Dairy cattle data was additionally disaggregated according to (a) the duration of animal monitoring (i.e. over the whole year vs over the lactation period) and (b) the monitored entity (herd vs individual cows).

To compare whether the two systems differ in terms of the entire feed rations, we run a permutational analysis of variance (non-parametric multivariate analysis of variance (MANOVA)) using a Euclidean dissimilarity index and 999 permutations to compute the significance tests. In addition, we tested the presence of significant differences between organic and conventional farming in the use of

each single feed category by using a non-parametric Kruskal–Wallis test—due to the non-normal distribution, tested through a Shapiro–Wilk test and residual check plots. All analyses were run on R \times 64 3.5.1, using lmer4 (Bates *et al* 2019) and vegan packages (Oksanen *et al* 2019).

3. Results

3.1. Animal productivity in organic vs conventional systems

Our results show that overall productivity per animal is 12% ($\pm 5\%$) lower in organic compared to conventional farming (figure 1). Despite high variability in the effect-sizes across animal species — especially for pigs and poultry layers (figure 1) — all livestock species exhibit a lower productivity in organic vs conventional farming. Among all livestock types, dairy cattle productivity, with a difference of -14% in organic compared to conventional farming, is the only one that reveals a significant difference. Note that similar results were observed by using non-weighted means — although with lower uncertainties — (figure S3) or when breaking down our dataset into research experiment vs farm monitoring (figure S4). Exception for this are dairy cows and poultry broilers for which experiment-based results yield no difference between organic and conventional management whereas lower organic productivity was reported in farm-based studies (figure S4). Note also that by breaking down our dataset into developed vs developing countries (figure S5), we found lower organic productivity in developed countries compared to conventional — in particular for dairy cows and poultry broilers. These results are in line with the statement that organic farming may perform well in many developing regions while drop in productivity is

higher in regions with high conventional productivity (Rigby and Cáceres 2001, De Ponti *et al* 2012, Kniss *et al* 2016).

Several factors may explain the observed productivity gaps, such as (a) use of less productive animal breeds, (b) higher vulnerability to animal diseases and parasites, in particular for monogastrics and (c) difference in feeding strategies, in particular for ruminants (longer grazing period, lower energy and protein density of the feed ration, higher share of fodder in the feed ration) (Van Wagenberg *et al* 2017, Rööß *et al* 2018). Our dataset did not make it possible to confirm any differences in the use of animal breeds and in vulnerability to diseases and parasites between organic and conventional farming systems, but it allowed to highlight differences in feed ration composition (see section 3.2).

3.2. Feed ration composition in organic vs conventional farming

Our results show that differences in animal feed ration composition are small for poultry, moderate for pigs and large for dairy cows when all eight of the detailed feed categories (table S2) are considered (figure 2(a)). These differences between organic and conventional were consistent independently of whether feed rations are expressed in mass (figure 2), energy or protein (figure S6).

More precisely, we found that the share of grassland products and hay is higher in organic than in conventional dairy feed rations (63% vs 44%, respectively). Similarly, the share of legume grains was higher in organic rations (table S2). In contrast, organic rations exhibit a lower share of non-legume grains (e.g. cereal grains: 21% vs 38%), non-legume by-products (e.g. wheat middling: 6% vs 8%), and legume by-products (e.g. soybean cakes: 0% vs 3%). These differences might be explained by a longer grazing season in organic dairy farming compared to conventional (Van Wagenberg *et al* 2017), a higher occurrence of legume grains in organic crop rotations (Barbieri *et al* 2017), especially in Europe, and a reluctance to use processed, costly concentrates such as legume and non-legume by-products. All these explanatory factors are clearly in line with the recommendations of organic regulations aimed at a high degree of self-sufficiency of organic livestock farming (Lampkin *et al* 2017). As mentioned before, moderate differences were observed between organic and conventional pig ration composition, with organic rations containing more legume grains (16% vs 9%), on the one hand, and the absence of feed from the 'other concentrate' category in organic rations, on the other hand. The 'other concentrates' represent 3% of the conventional pig ration and contain feed such as synthetic amino acids. These synthetic amino acids are banned in organic livestock feed rations, thereby probably contributing to the observed lower animal

productivity (Guoyao *et al* 2007) as reported in figure 1.

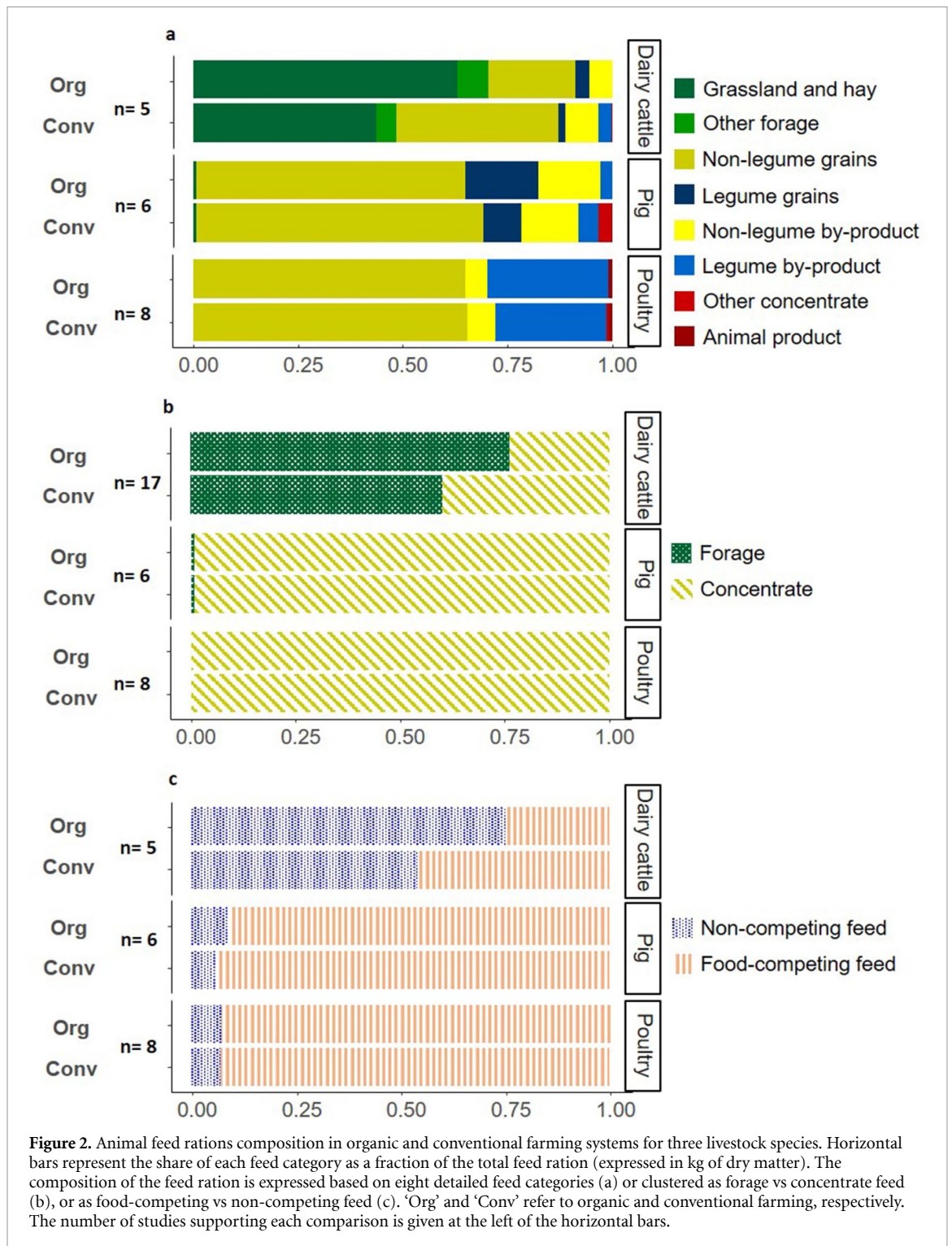
When considering feed rations expressed in terms of forage vs concentrate feed (figure 2(b)), we found that rations of organic dairy cattle contain significantly more forage products than for conventional dairy cattle (76% vs 60%, respectively), a result confirmed when expressing feed rations in energy and protein (tables S3 and S4). Organic farmers often use a higher share of fodder to feed their animals due to (a) the low availability of organic concentrate feed (lower diversity and higher prices than for conventional ones) (Flaten and Lien 2009, Escribano 2018), and (b) organic regulation requirements that set a minimum share of forage in ruminants' diets (Lampkin *et al* 2017). This higher use of forage and limited utilisation of concentrates probably contribute to the productivity gap between organic and conventional dairy cattle found in figure 1 (Aguerre *et al* 2011).

Finally, when considering feed rations expressed in terms of food-competing vs non-competing feed (figure 2(c)), we found a 45% lower share of food-competing feed in the organic dairy cattle feed ration compared to conventional livestock feeding (25% vs 46% respectively). Similar results are found when considering the energy and protein feed ration (tables S3 and S4). However, no differences can be observed regarding pigs and poultry production, with approximately 92% of the ration potentially competing with human food in both organic and conventional farming (table S2).

3.3. Feed-use efficiency in organic vs conventional farming

Our results show that feed-use efficiency (the ratio of the amount of animal product to the animal feed intake), when calculated over the entire feed ration, is 14% ($\pm 8\%$) lower in organic compared to conventional farming (figure 3(a)). This lower feed use efficiency in organic compared to conventional is especially significant for dairy cattle ($-11 \pm 9\%$) and poultry broilers ($-47 \pm 10\%$). Similar results were observed by using non-weighted means (figure S7) — although with smaller uncertainties — when feed-use efficiency is calculated based on the energy and protein feed ration (figure S8) or when disaggregating our dataset into studies based on research experiment vs farm monitoring (figure S9).

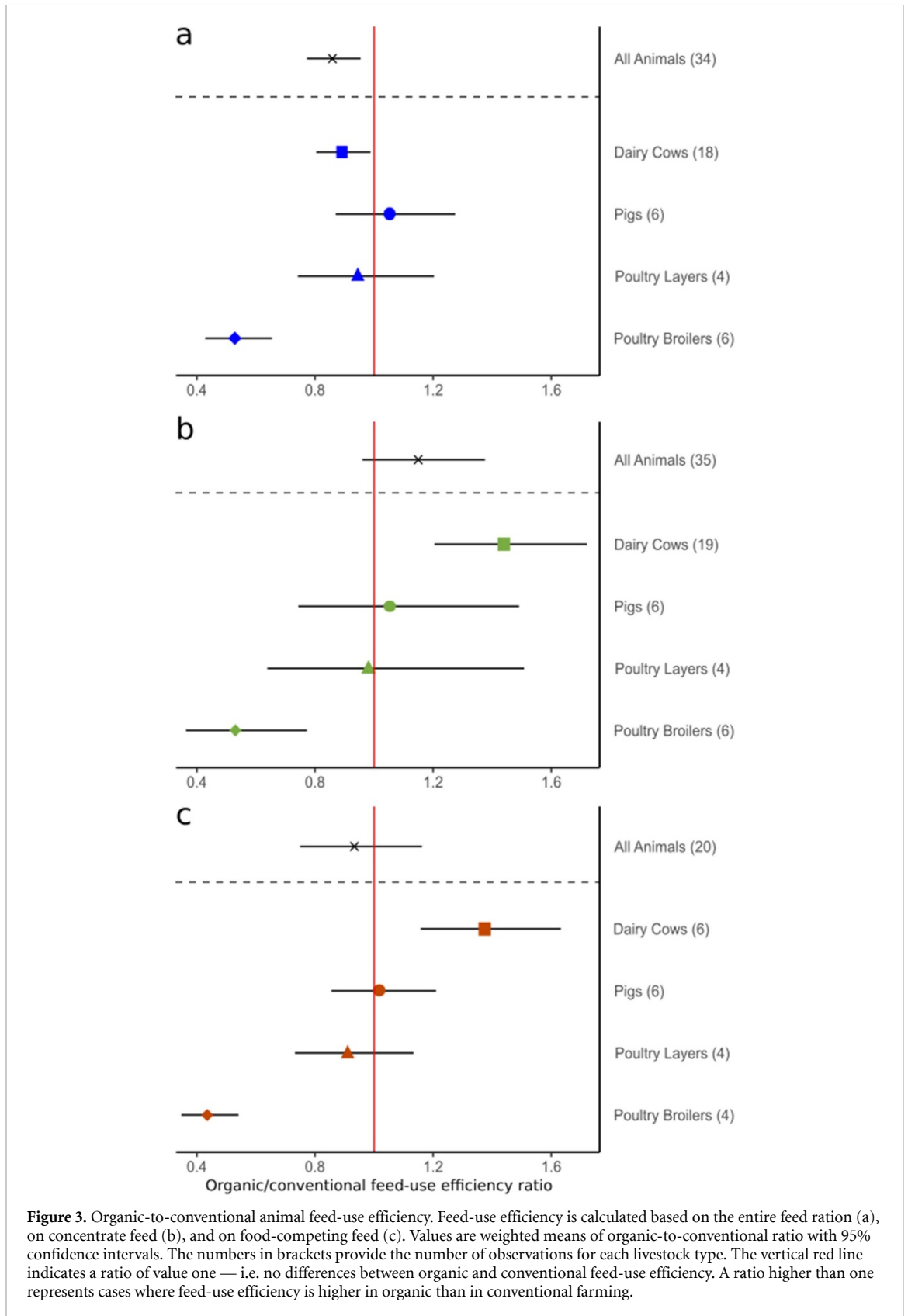
The lower feed-use efficiency for organic dairy cattle may be partly explained by differences in feeding strategies. We found a higher share of rough forages in animal diets in organic compared to conventional farming (figure 2). Forage based diets are known to be often less balanced than grain based diets (Voelker *et al* 2002, Brito and Silva 2020), leading to reduced milk yield. However, in those forage based diets, the negative effect of lower milk yield on feed-use efficiency might be compensated (though



not completely) by a lower feed intake: as rough forages are less digestible, they require more space and time in the cow’s rumen, leading to lower ingestion of other feeds (Voelker *et al* 2002). Milk yield reduction can be exacerbated if feeding animals with rough forages comes with more grazing. Indeed, grazing costs more energy to the animals than other feed intakes, leading to reduced energy availability for milk production (Kaufmann *et al* 2011). Although our dataset did not provide information on grazing management between organic and conventional dairy cows,

we found both a reduced milk yield and a higher forage share in the organic dairy rations compared to conventional ones. Therefore, lower feed-use efficiency for organic dairy cattle (figure 3(a)) may be explained by a lower animal productivity due to a coarser and less energetic forage-based feed ration (figure 2).

Note though that feed-use efficiency differences between organic and conventional livestock production may also be explained by differences in the way the farm is managed (Mottet *et al* 2017). We



observed differences between studies based on monitoring the entire herd vs based on monitoring each individual cow (figure S10). Differences can also be observed when data are taken from observations over the lactation period only vs over the entire year (lactation + resting period). Organic dairy herds show a

lower feed-use efficiency compared to their conventional counterparts ($-15 \pm 6\%$). A similar trend is observed for organic dairy cattle monitored over a year period compared to their conventional counterparts ($-13 \pm 10\%$), whereas no differences are observed between organic and conventional dairy

cattle monitored over a lactation period (figure S10). Different hypotheses can be made to explain those results based on (a) differences in the number of non-productive animals, (b) differences in the length of the resting period between two lactations, and (c) more marginally, the fact that dairy cattle might be fattened before being sent to the slaughterhouse. As for this last hypothesis, our dataset does not provide sufficient information to confirm or invalidate it, although we observed a 57% lower replacement rate in organic compared to conventional dairy herds (see supplementary methods about replacement rate estimation). A lower replacement rate implies a lower number of unproductive animal in a herd (such as calves and heifers), possibly leading to a higher feed use efficiency of the herd as a direct consequence of the smaller number of unproductive animals. Our results show otherwise, suggesting that the number of non-productive animals is not the main driver of feed-use efficiency in organic dairy herds. Instead, the fact that organic dairy cows have a lower feed-use efficiency over the year compared to their conventional counterparts suggest that organic dairy cows have a longer resting period between two lactations, which might explain the differences in feed-use efficiency between organic and conventional dairy herds.

In contrast, the difference in feed-use efficiency for poultry broilers cannot be explained by a difference in animal productivity (which was non-significantly different in organic vs conventional farming, see figure 1). Data on poultry life span showed a 45% longer lifespan for organic vs conventional poultry broilers in our database. This result is in agreement with organic regulations that do not allow broiler slaughtering before 81 d (Rezaei *et al* 2018). Consequently, organic broilers need to be fed over a longer time, which leads to lower feed-use efficiency. When controlling slaughter age (two of our comparisons were based on an experiment where organic and conventional poultry were both slaughtered at the same age), similar feed-use efficiencies were found between organic vs conventional (data not shown) thus confirming effect of slaughter age.

Interestingly, our results show that these differences between organic vs conventional farming are modified when feed-use efficiency was calculated based on concentrate feed or on food-competing feed. Concentrate feed-use efficiency generally exhibited a higher — although not significant — value for organic animals (figure 3(b)). In particular, organic dairy cattle are 44% ($\pm 23\%$) more efficient in their use of concentrate feeds than their conventional counterparts (figure 3(b)), a result explained by the lower concentrate consumption in organic dairy cattle production (figure 2(b)). We found a similar result when feed-use efficiency was expressed in terms of food-competing feed, with organic dairy cattle being 37% ($\pm 26\%$) more efficient in their use of food-competing feed compared to their conventional

counterparts (figure 3(c)). In contrast, for pigs and poultry, feed-use efficiency does not significantly change when calculated based on the entire feed ration, the concentrate feed or the food-competing feed (figure 3), a result explained by those animals being mainly fed with concentrate, food-competing feeds (figure 2). Finally, by breaking down our dataset into developed vs developing countries we found a consistent—although rarely significant—greater feed-use efficiency in developed countries (figure S11). This result is probably related to more precise feeding management in developed countries, as well as to scarce data regarding developing countries.

4. Discussion

When comparing the sustainability, profitability and food security impacts of organic compared to conventional farming systems, the yield gap between the two systems is a key issue (Connor 2008, Gattinger *et al* 2012, Skinner *et al* 2014, Reganold and Wachter 2016). To the best of our knowledge, this study is the first global comparison to provide quantification of the productivity gap between organic and conventional livestock production. More importantly, we provide here a first comparison of organic vs conventional livestock's feed ration composition and feed-use efficiency in a systemic way. By calculating partial feed-use efficiencies based on concentrate and food-competing feed, our analysis also provides critical values to assess the impact of organic livestock production on the feed/food competition in a food security context.

Feeding strategies and animal productivity are closely related. A higher forage-to-concentrate ratio often result in lower animal productivity (Voelker *et al* 2002, Aguerre *et al* 2011), whereas the use of synthetic amino acids often promotes animal growth (Eriksson *et al* 2010). Our results show similar trends, with (a) lower animal productivity under organic compared to conventional farming and (b) differences in the feed ration composition that likely impact animal productivity. Different feeding strategies contribute to the differences we found in feed-use efficiency as well, although the main driver probably also lies in the management practices applied (such as age at slaughter and reproduction cycle management).

Our results have different implications for the development of organic farming and for assessing its potential to deliver food in a sustainable manner. First, the overall lower productivity of organic animals contrasts with the observed increasing consumption of livestock products at the global scale, especially in developing countries (Tilman and Clark 2014). Therefore, farming the planet organically would make it difficult to satisfy animal product demand, thus reinforcing the global mitigation of animal product demand as a key leverage factor to achieve global food security (Erb *et al* 2016, Muller *et al* 2017). Second,

our results highlight how the organic vs conventional livestock affect and contribute to the feed/food competition. Livestock production uses one-third of the global cereal production (Foley *et al* 2011), with considerable implications for human food supply. An increase in the feed-use efficiency of food-competing feed is essential to reduce cereal use by livestock animals and to enhance global food security. Providing indicators and data on the impact of organic farming on feed/food competition is therefore highly needed to assess its potential to ensure food security. Our results show that this impact strongly depends on the animal species and type considered. Organic poultry is less efficient in its use of food-competing feed (improvement of this might come from the selection of breeds more adapted to organic conditions (Röös *et al* 2018)), whereas the opposite is observed for dairy cattle (that strongly rely on forage products for feeding). Those results are in line with the outcomes of scenarios that explore more sustainable ways of managing livestock production globally (Röös *et al* 2016, van Zanten *et al* 2016, Koppelmäki *et al* 2021). Most of those scenarios converge on the need to feed ruminants a grass-based diet in order to alleviate the feed/food competition. Our results show that organic dairy cattle management already apply those recommendations. Third, the forage-rich diets of organic dairy cattle that we highlighted is highly consistent with previous studies showing a higher share of temporary pasture in organic crop rotation compared to conventional ones (Barbieri *et al* 2019, Smith *et al* 2019). Rotated, temporary pastures have been reported to have environmental benefits — especially in terms of carbon sequestration — (Paustian *et al* 2016, Dumont *et al* 2019, Horrillo *et al* 2020, Martin *et al* 2020) thus helping to offset part of livestock greenhouse gas emissions. Therefore, by being more often grass-based than in conventional farming, organic dairy systems contribute to more sustainable and climate-friendly ways of farming.

Note however that the significance of our results must be balanced with their limitations. The scientific literature on feed-use efficiency between organic and livestock production remains limited and often provides incomplete data (on variance or detailed feed ration), with some consequences for our study implications. First, weighting studies by their internal variance was made impossible, thus preventing to account for individual study accuracy and precision. However, weighting studies by their number of observations is a satisfactory alternative that we applied here and similar results were obtained by using weighted and non-weighted methods, thus confirming the robustness of our approach. Second, though we consider geographical variability by disaggregating our dataset between developed vs developing countries, we could not consider more regional variability. Our data set is mainly focused

on Europe and Middle East (figure S2), and this specificity must be accounted for when using our results. Clearly, more results are needed from developing countries to better capture effects of organic management in those regions. Finally, some livestock categories are under-represented in the literature, with a very limited number of studies on small ruminants and on beef cattle production, thus preventing to extend considerably our study beyond the four livestock species and types considered here. For instance, based on the very few data available in the literature (in Italy and in India, Singh *et al* 2010, Buratti *et al* 2017), we found that the productivity gap between organic and conventional animals was lower (and closer to zero) for beef than for dairy systems. This result is in line with the fact that, at least in Europe, beef systems are often managed less intensively (whether organic or conventional) than dairy systems. Therefore, these dataset limitations must be accounted for when using our results as inputs in global models that explore the consequences of organic farming upscaling and its impacts on food security and the environment. If these limitations are taken into consideration, our results could be of strong interest for models exploring such upscaling scenarios — such as the BioCBioBaM (Erb *et al* 2016) or the sustainability and organic livestock (SOL) models (Muller *et al* 2017) — which currently consider no differences between organic and conventional livestock production. Implementing our results in those models will improve their accuracy about feed demand and animal product supply.

Finally, the limited size of our dataset highlights the need for more standardised procedures when comparing and reporting data concerning organic and conventional livestock production and feeding strategies, e.g. by detailing the animal feed ration composition. In addition, a unified classification of feed products and their potential to be used in human nutrition (currently and considering technological improvements in energy and protein extraction for human use) would be a big help to calculate appropriate food-competing feed-use efficiencies (Mottet *et al* 2017, Laisse *et al* 2018). Adopting a production system approach in studies reporting animal feed use (e.g. by detailing animal number of lactations or herd replacement rate) would be of great benefit to consider the different factors that influence animal productivity and system feed-use efficiency.

5. Conclusion

This first global comparison on organic vs conventional livestock production highlights a clearly lower level of animal productivity and feed-use efficiency of organic compared to conventional livestock farming. Differences in productivity are likely to be explained by differences in feeding strategies for which we

provided some evidence. Differences in feed-use efficiency are likely to be explained by differences in livestock system management (such as herd structure and slaughter age) in addition to feeding effects. Such findings may result in more land required by organic livestock farming compared to conventional farming to achieve the same level of animal production. Notwithstanding, our results also show that organic dairy cattle are less in competition with human food production due to their higher food-competing feed-use efficiency, with strong implication for land use and human food production. Even though additional research efforts are needed to consolidate our findings, those are key to understanding and assessing the impact that organic livestock upscaling may have on global food security and farming sustainability.

Data availability statement

The authors declare that the main data supporting the findings of this study are available within the article and its supplementary Information files. Extra data are available from the corresponding authors upon request.

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Conflicts of interest

The authors declare no competing interests.

Authors' contributions

UG, TN and SP designed the study; UG collected the data and performed the statistical analysis; all authors were involved in the interpretation of results and contributed to writing and revising the manuscript.

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