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PAPER

Estimating methane emissions from manure: a suitable case for treatment?

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Abstract

Methane from livestock is a significant source of greenhouse gas emissions. Under the UN Framework Convention on Climate Change (UNFCCC), Annex I countries' National Inventories report emissions from cattle as enteric or from manure management at ratios of between 3:1 and 9:1 depending on country and cattle type. Field research generally supports the inventories' assumptions about enteric emissions, but these ratios have focused interest on enteric emissions and diverted attention away from those from manure management. Official calculations about manure management emissions factors are more varied than those for enteric emissions and evidence from field measurements suggests inventories may be underestimating manure management emissions especially in the dairy sector. This paper has three objectives. First, it reviews the science underpinning the international framework for estimating methane emissions from manure management. Second, it presents data from two dairy farms in south-west England where measured emissions of methane from slurry storage facilities are found to be four to five times greater than the assumptions in the UK's inventory. If these measurements were representative of the UK, the implication is that total methane emissions from the UK dairy herd would be over 40% greater than the level reported to the UNFCCC and the proportion of total methane emissions from dairy cows arising from manure management would be almost a half rather than less than a quarter. Finally, the paper assesses the potential value if methane were captured from slurry storage facilities. Its value as a biogas is estimated to be £500 million per year for the UK dairy industry (at forecourt diesel prices). The paper concludes that the scale of emissions and the potential economic value of lost biogas are sufficient to warrant urgent research and action to reduce emissions from manure management with the beneficial prospect that a valuable new income stream for farm businesses could also be realised.

1. Introduction

The COP2024 meeting in Dubai highlighted the importance of food, agriculture and land use in global climate change, with methane emissions from the livestock sector a major source of greenhouse gases (GHGs). Globally the agri-food system contributes a third of total GHG emissions (Crippa *et al* 2021). Farm livestock, and especially ruminant animals, are a prominent source of methane emissions from agriculture and, based on current Intergovernmental Panel on Climate Change (IPCC) methods of estimation, account for 12%–14.5% of all human induced GHG emissions (Food and Agriculture Organisation 2023a, p 1, 2023b, p xi). Livestock emissions are generated by enteric fermentation (emissions directly from the animal themselves through their digestive systems) and from manure management. Research has tended to focus on enteric emissions, and especially changes to breeding and feeding. Less prominent have been emissions from manure management practices.

National estimates of methane emissions from livestock are informed by a framework developed by the IPCC in 2006 (IPCC 2006). The framework's evidential base is a small set of studies from the 1970s to 1990s. The framework sets out the methods by which National Inventory compilers can calculate emissions factors and estimates of total methane emissions from agriculture for their submissions to the United Nations Framework Convention on Climate Change (UNFCCC). In recent years, there has been increasing scientific interest in the robustness of measurements of methane emissions from livestock (O'Brien and Shalloo 2021, Tedeschi *et al* 2022). This paper reviews the basis for estimating methane emissions from livestock, and particularly dairy cows. It first briefly explains the significance of livestock farming as a methane source. It examines the IPCC's framework for estimating methane emissions from livestock and the scientific basis underpinning it. It reviews international evidence from field monitoring which calls into question national estimates of emissions from manure management and takes the UK as a case study to explore how estimates for methane emissions from manure management are arrived at. Multiple benefits could be generated from more effectively controlling methane emissions from livestock manures, including reduced GHG emissions but also economic benefits from utilising a wasted resource. The paper concludes with a proposed research agenda to help address the risk that methane emissions from manure management may be being under-estimated.

2. Methane as a greenhouse gas

Climate change is a pressing challenge. The World Meteorological Society calculates that there is a 66% chance that the 1.5 °C warming target enshrined in the Paris Agreement is likely to be exceeded in the next five years (Jones 2023). Global average temperature is rising at a rate of 0.175 °C each decade, and methane (CH_4) is a significant contributor to current warming (IPCC 2006), with methane levels in the atmosphere rising rapidly compared to the pre-modern period (Mitchell *et al* 2011). Methane is around 80 times as warming as carbon dioxide (CO_2) over a 20 y period, although it does not persist in the atmosphere for as long. The UN's Food and Agriculture Organisation (FAO) reports that the global ruminant population increased by 66% between 1960 and 2017 (FAO 2023b, p 1). Forecast trends are for the global demand for animal products to increase by a further 60%–70% by 2050, as economic development among developing countries drives growing meat and dairy consumption (Makkar 2018). Reducing methane emissions can be a speedy and cost-effective tool in combatting global warming (Environmental Investigation Agency 2023). In 2021, the Glasgow COP26 Conference agreed a Global Methane Pledge which committed a group of high methane-emitting participants (including the US, the EU and the UK) to reduce global methane emissions by at least 30% by 2030.

In agriculture, reported methane emissions largely come from rice production and ruminant animals. Ruminant emissions comprise those from enteric fermentation and from manure management—the storing, handling and spreading of slurry and farmyard manure. National Inventories to the UNFCCC show that total methane emissions from cattle are estimated at around 8000 kt in the US, 1600 kt in Australia, 1300 kt in France and 770 kt in the UK, with dairy cows producing significantly more methane per head than beef cattle. Inventories show enteric fermentation typically accounting for 75%–90% of total methane emissions from dairy cows[4]. This has left emissions from manure management as a secondary, and relatively obscured concern. While agricultural emissions can be a major contributor to countries' methane emissions totals, science and innovation efforts have tended to focus more heavily on enteric fermentation. For example, a recent FAO report into methane emissions from agriculture contained discussion of 31 alternative strategies for reducing enteric emissions, over almost five times as many pages as the 13 strategies for reducing emissions from manure management (FAO 2023b, pp 49–139). At the COP28 in Dubai in December 2023, a Ministerial announcement on the Global Methane Pledge covering 155 countries launched an Enteric Fermentation R&D Accelerator with $200 million of funding, emphasising that 70% of livestock emissions come from enteric fermentation (European Commission DG Energy 2023).

Reducing methane emissions from livestock production has been seen as a difficult problem compared to, for example, reducing emissions from the energy sector. However, reducing methane emissions from farm livestock could have a large and speedy impact on reducing warming. At the same time, there is potential to capture methane from manure management and harness it as a resource to replace fossil fuels. If methane is used in a combustion process, it is converted to CO_2, but with the impact of emissions considerably

[4] This range is derived from analysis of the National Inventory data for Australia, Canada, Denmark, France, Germany, Ireland, Netherlands, New Zealand, UK and USA.

reduced[5]. Methane can also be used in fuel cells. In the UK, according to our measurements reported in this paper, dairy cows produce an estimated 170 kg per head per year of methane from slurry. For an average-sized herd of 140 cows, this has the same energy potential as 33 055 l of diesel fuel per year which, at £1.59 a litre on the forecourt, would be worth a benefit of £52 470 per year[6]. The CO_2 saved from the displaced diesel equates to 86.2 tonnes of emissions, while the CO_2 emitted from using methane as a fuel source would be 65.5 tonnes for an average dairy herd, meaning a net reduction from agricultural fuel use of 21.8 tonnes[7]. Using captured methane as an alternative fuel source would produce a net saving of 2953 tonnes of CO_2e in the first year for such an average UK dairy herd.

3. Calculating methane emissions from livestock

The scale of methane emissions from manure management have been obscured because of the IPCC's approach to calculating emissions from livestock. Typically, emissions from enteric fermentation from cattle have been estimated to be between six and nine times greater than emissions from manure management. The IPCC produced guidelines in 2006 to inform national GHG calculations for agriculture and set out a 3-tiered approach (IPCC 2006). *Tier 1* methods are the simplest and based on average annual temperatures and geography. *Tier 2* is a bottom-up calculation based on formulae using emissions factors and applies country- or region-specific data for the most important livestock categories. *Tier 3* uses higher order methods where models and inventory measurement systems are more tailored to address specific national circumstances and based on field measurements.

The IPCC livestock emissions guidelines are contained in an 87-page section, with updates issued in 2009, 2013, 2018 and 2020 (IPCC 2006)[8]. They contain equations to calculate the volume of emissions from different livestock species and management practices. Some 15 pages of IPCC guidance focuses on methane emissions from manure management, covering the choice of method, emission factors, activity data and uncertainty assessments (IPCC 2006, chapter 10, pp 35–50). The formula for calculating methane emissions from manure management is as follows (IPCC 2006, equation 10.22):

$$\mathrm{CH}_{4\mathrm{Manure}} = \sum_{(T)} \left(\frac{\mathrm{EF}_{(T)} * N_{(T)}}{10^6} \right).$$

Where:
$\mathrm{CH}_{4\mathrm{Manure}} = \mathrm{CH}_4$ emissions management, for a defined period Gg CH_4 yr^{-1}
$EF_{(T)}$ = emission factor for the defined livestock population, kg CH_4 head^{-1} yr^{-1}
$N_{(T)}$ = the number of head of livestock species/category T in the country
T = species/category of livestock

Tables in the IPCC guidelines present emissions factors for different livestock species at different annual average temperatures across nine regions. For western Europe, emission factors for dairy cows range from 21 kg CH_4 head^{-1} yr^{-1} in the coolest annual average temperatures (less than 10 °C) to 92 kg CH_4 head^{-1} yr^{-1} in the warmest (greater than 28 °C) (IPCC 2006, p 10.38). The Tier 2 method requires in-country data on the characteristics of manure and management systems. Manure characteristics include volatile solids (VS) in the manure and the maximum amount of methane able to be produced from that manure (B_o). VS can be calculated from data on feed intake and digestibility or can be derived from direct measurements. The methane conversion factor (MCF)—an important discounting factor which estimates the proportion of methane-producing potential emitted in different systems—can vary significantly. Manure managed as a liquid slurry under warm conditions for an extended period promotes methane formation and these sorts of conditions can have high MCFs of 65%–80% (IPCC 2006, p 41). Under Tier 2 calculating emissions from systems involves determining a weighted average for MCF using the manure systems for different regions using the following formula (IPCC 2006, equation 10.23):

$$\mathrm{EF}_{(T)} = \left(\mathrm{VS}_{(T)} * 365\right) * \left[B_{0(T)} * 0.67\mathrm{kg}_{\overline{m3}} * \sum_{S,k} \frac{\mathrm{MCF}_{S,k}}{100} * \mathrm{MS}_{(T,S,k)} \right] \ldots$$

[5] Assuming a global warming potential for methane 80 times that of CO_2, combustion of 1 kg of methane generates 2.75 kg of CO_2, which means the warming impact of emissions is reduced by 77.25kgCO_2e.

[6] UK farmers enjoy subsidised 'red diesel' which is priced at around 80p per litre, meaning the saving for a UK farmer from an average sized dairy herd would be £26 235 per year.

[7] The CO_2 emissions per litre are 2.6391 kg(CO_2)/ltr. The equivalent litres of diesel not used are 33 055, so 86 236 kg are saved and emissions from the CH_4 combustion (equivalent energy) are 65 450 kg. The net reduction is then 21 787 kg.

[8] The various updates are all published alongside the original 2006 document and accessed through the same link.

where:

$EF_{(T)}$ = annual CH_4 emission factor for livestock category T, kg CH_4 animal^{-1} yr^{-1}

$VS_{(T)}$ = daily volatile solid excreted for livestock category T, kg dry matter animal^{-1} d^{-1}

365 = basis for calculating annual VS production, days yr^{-1}

$B_{o(T)}$ = maximum methane producing capacity for manure produced by livestock category T, m^3 CH_4 kg^{-1} of VS excreted

0.67 = conversion factor of m^3 CH_4 to kilograms CH_4

$MCF_{(S,k)}$ = methane conversion factors for each manure management system S by climate region k, %

$MS_{(T,S,k)}$ = fraction of livestock category T's manure handled using manure management system S in climate region k, dimensionless

Taking the case of a dairy cow in the UK, with an annual average temperature of 10 °C, the IPCC's Tier 1 approach would produce a calculation of methane emissions of 210 kg per year from manure management. If the manure is stored for a period covering some of the summer months, the emissions would be estimated at 430 kg per year. Using Tier 2, the first stage of the calculation is to establish the maximum potential methane that could be produced from the VS (VS^*B_0), multiplied by density and number of days. The UK figures for the most recent National Inventory record VS of 5.3 and B_0 of 0.24. The second part of the calculation is to apply the MCF as a discounting factor and a measure of the fraction of livestock handled by the manure system. Using the data in the most recent National Inventories, the emissions of methane per head of dairy cattle are 834 kg per year in Denmark, 333 kg in Canada and 311 kg in the UK. The US and Denmark are heavily represented among scientific studies of methane emissions from manure management and seem most interested in developing the capacity to pursue the Tier 3 methodology for this emissions source. The fundamental potential for methane emissions from livestock is relatively uncontentious. However, the process of discounting through the use of the MCF, and its aggregation, is prompting concern about the accuracy of the calculation in National Inventories and, therefore, the official estimates of methane emissions from farm livestock. Confidence in the appropriateness of mitigation measures depends on confidence in the science of measuring emissions that underpins international guidance on calculations for national inventories.

The Tier 2 method tends to produce a lower emissions estimate than Tier 1. Data in National Inventories show wide variations between Annex I countries in the calculated estimates of methane emissions per dairy cow per year using the Tier 2 method. There is a relatively strong degree of consensus around emissions from enteric fermentation across different countries, which are usually calculated to make up 75%–90% of all methane emissions from dairy cows, for example, but these proportions serve to downplay the significance of emissions from manure management. Indeed, accounts of livestock emissions commonly disregard emissions from manure management altogether and consider just enteric fermentation, including work from influential consultancies such as McKinsey & Co (2021). The result is that emissions from manure management do not receive the same level of attention as those from enteric fermentation.

4. Confidence in methane emissions calculations

4.1. The international literature

The science underpinning the IPCC's formulae for methane emissions dates back decades. Influential work in the mid-1990s (Johnson and Johnson 1995) is based on calculations first made in the 1970s (Allen and Lowery 1976). The literature assumes that ambient air temperature is an important determinant of methane emissions from manure management, and this is incorporated into the IPCC calculations using measures of annual average temperatures. Recent research has sought to establish the rates of methane emissions from farm livestock. A 2014 global meta-analysis compared field measurements of methane and nitrous oxide emissions with inventory values among 38 studies (Owen and Silver 2014). It noted that the IPCC's emissions factors for dairy cattle were largely based on a small number of lab or pilot-scale studies. The analysis found that measured emissions from slurry tanks and ponds were around three times higher than modelled emissions but noted variability in measured values. It concluded that emissions factors in inventories are generally underestimating emissions. 'Top–down' studies of methane emissions, using aircraft and tower measurements of methane concentrations in the environment, estimated that methane emissions from livestock measurements were likely to be twice as high as inventory values. The study was conducted before the common use of the latest measurement techniques (such as plume measuring), so the measurements in the meta-analysis may be less accurate than more recent work. It was also carried out before the IPCC's most recent revisions to its framework in 2018 and 2020.

Recent research in Canada included detailed measurements of methane emissions from a covered slurry lagoon (Johannesson 2018). It found that mixing slurry increased emissions and if temperature dips below 5 °C for any length of time the emissions stopped, with temperature needing to rise to greater than 18 °C–20 °C for emissions to recommence. The study found that the average time that slurry was stored was

6–8 months, so summer temperatures always had some influence on emissions from the stored slurry. It suggested that median summer temperature would be a more appropriate measure for National Inventory calculations than average annual temperature. It calculated that VS were 7.8 kg dry matter per head per day, rather than the 5.8 assumed in Canada's National Inventory. The 'practices factor' (MCF * MS in the formula for calculating emissions factors) should be 45% and that would lead to a good correlation with the National Inventory data. The research suggested 206 kg of methane were emitted per dairy cow per year through manure management, compared to Canada's Inventory figure of 150 kg per cow per year. Notably, the discount factor of 0.45 compared with typical discount factors of 0.9 in inventories. It also found that annual average ambient air temperature is not a significant driver of emissions.

Arndt *et al* (2018) carried out detailed analysis of animal and manure management practices on two dairy farms in California. Different measurement techniques were used to understand emissions compared to inventory values. Measurements were taken using a sensor near major sources, and accounting for wind direction and ambient air measurements. Measurements were also made using a tracer gas dispersion method with a tracer gas sensor near areas on the farms expected to be significant methane sources. Aircraft measurements were also made using concentric flight paths around the facilities. The researchers found that the measurement techniques gave similar methane emissions results. The ratios of enteric to manure methane emissions on one dairy farm were 21:79 and 46:54 during summer and winter, respectively. The corresponding values on a second dairy farm were 31:69 and 74:26. These results suggest that manure management on the first dairy farm might have contributed more than the 55% of whole-facility's methane emissions estimated by the inventory.

More recently, Amini *et al* (2022) measured emissions at 135 Californian dairies using aircraft and vehicle-based plume measurements in summer and autumn. Measurements were compared against California Air Resources Board (CARB) emissions factors derived from the IPCC. The ratio of measured emissions to calculated emissions factors was 1.1, with similar emissions found in summer and autumn. The authors hypothesise that the increasing temperature in summer is offset by lower wind speeds. CARB emissions factors of 332 kg and 144 kg $CH_4.hd^{-1} . yr^{-1}$ for anaerobic lagoon and enteric fermentation emissions are consistent with previous field studies that reported a range of 368 kg $\pm$ 193 kg $CH_4.hd^{-1} . yr^{-1}$ (mean $\pm$ standard error) for anaerobic lagoons (Owen and Silver 2014), and 137 kg $\pm$ 10 kg $CH_4.hd^{-1} . yr^{-1}$ (mean $\pm$ standard error) for dairy cow enteric fermentation (Kinsman *et al* 1995, Sun *et al* 2008, Bjorneberg *et al* 2009, Hamilton *et al* 2010, Leytem *et al* 2011, Arndt *et al* 2018). The emissions factors show much higher emissions from manure (332 kg) compared to enteric fermentation (144 kg), noting that the study completed only site-wide measurements, calculating emissions factors from study data and then comparing with total emissions.

Vechi *et al* (2022a) measured emissions from nine Danish cattle farms using tracer dispersion methods. Five to six measurement campaigns were carried out at each farm, most of which were dairy farms. Whole farm methane emission rates ranged from 6.1 to 245.3 tonnes per year and the highest measurements mapped onto locations with the highest numbers of animals. Emissions from dairy cattle farms were, on average, 62% higher than for beef farms. The study estimated that, averaged across all farms, the IPCC approach produced estimates 35% lower than those derived from direct measurements. A similar study of pig farms in Denmark demonstrated that the problem of underestimation through the IPCC approach applied to pigs too (Vechi *et al* 2022b).

Vechi *et al* (2023) also used ground-based measurements using Fourier transform infrared spectrometry, with methane calculated indirectly from nitrous oxide:methane ratios. They conducted surveys in May and October in California, covering 14 dairy farms. They found methane emissions were in general greater than inventory emissions for California, on average by 60% but with high variability between sources. Liu *et al* (2023) recently compared methane emissions measurements to inventory estimates in Cyprus focussing on waste and agriculture as the nation's two primary methane sources. Measurements of landfill and cattle farms were completed using mobile measurements and gaussian trace modelling in 24 surveys (October 2020–September 2021). Measurements were compared with the IPCC Tier 2 calculations for dairy cattle. Manure management practices are not discussed in their paper, but the study found that methane emissions from dairy sites were 40% higher than inventory values, although measurements were in the lower range of the estimated confidence interval for inventory values. Overall, studies suggest that field measures of enteric fermentation broadly accord with the IPCC's framework for estimating emissions from this source. However, field measurements of emissions from manure management suggests levels of emissions greater than the IPCC framework's estimate by factors ranging from 3 to 9.

4.2. Field measurements from the UK

Methane emissions were measured from the slurry storage facilities on two farms in Cornwall in south-west England over a 51 week period during 2022–23 (see figures 1 and 2). On these farms, slurry is added to the

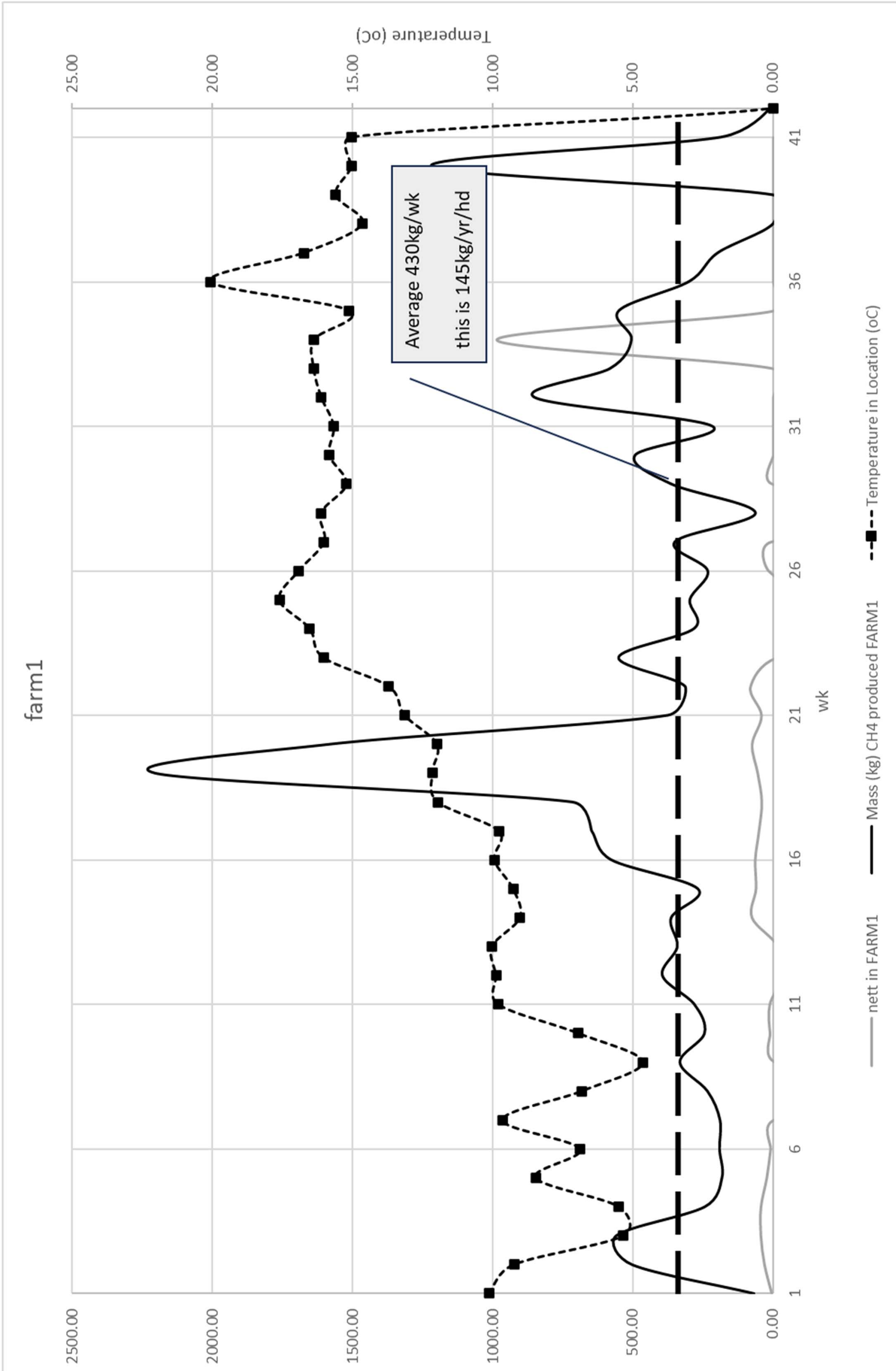

Figure 1. Methane Emissions from Farm 1, Cornwall, England.

storage facility from the cattle housing and milking areas. The storage facilities are covered as illustrated in figure 3. The cover has two parts. A lower part captures the raw gas through a selective membrane. The raw gas is then processed by a Gas Filtration Skid. The skid removes moisture and hydrogen sulphide and puts the gas into an upper space in the cover. This lower pressure store is emptied by a Compressed Fugitive Methane system. The system removes carbon dioxide to a maximum level of 10% and compresses the methane for bottling. Regular purity checks have shown that the gas is usually greater than 94% methane ($<$6% CO_2). The process outline is depicted in figure 4. The gas in the bottles is measured by mass on scales. The mass of gas elsewhere is derived from time of pumps on and validated volume flow and defined purity. Data collected covers raw gas pressure, flared cleaned gas (as the supply chain for the gas is currently being built and so 20% is flared), cleaned and compressed gas and the volume of slurry in and out.

Figures 1 and 2 show the methane emissions from these two dairy farms over a year, alongside air temperature. Figure 1 is shown without the solar and rainfall traces to emphasise the lack of correlation with air temperature. The mesophilic range anaerobic digestion process is most active when the target media is between 25 and 30 °C and tends towards increasing inactiveness below 15 °C. That considered, the first half year air temperature is below 15 °C and so we would not expect considerable methane being produced. Further, when the air temperature increases in the summer months there is not significant increase in production. Indeed, the grey line at the bottom of the graph shows the nett flow into and out of the storage facility and hence mixing due to flow shows a delayed production. From the graph this appears around six weeks after the nett flow. (Note this is a new facility, and so there was only flow into it during the period when measurements were taken.

Figure 2 shows measurements from an older facility so there are both positive and negative flows. Large flows create agitation leading to a subsequent large flow. Again, there seems to be little correlation with air temperature. However, rain cools the slurry and solar load directly warms. High rainfall usually sees a dip in production after the event and peaks in solar load match the production.

In terms of heating up, if we imagine a column of air above the slurry then the cool air will settle above the slurry and hence the differential to the slurry is lower than expected and heat transfer is only by conduction. Further, the heat can only be transferred down into the slurry by conduction. In terms of cooling, the cooling air is more effective as the slurry warms the air making it more buoyant and hence convective cooling occurs (Atkins *et al* 2022). Further, with wind it may evaporate if un-covered. Mixing helps turbulence and mixes in air to the slurry which can stop anaerobic digestion but leads to greater microbial load and hence the delayed emission peak. Solar load then directly radiatively heats the slurry and surrounding ground through soil transfer with below ground level stores.

Our results suggest little relationship between air temperature and production of methane from the slurry storage facilities but do illustrate a complex correlation between solar load, air temperature, rainfall and mixing. This suggests, as in Canadian study, that the simple use of air temperature in Tier 1 of the IPCC framework is a poor measure for estimating methane emissions from manure management. The Tier 2 method, which currently records 38 kg of methane per dairy cow emitted through manure management in the UK, also represents a significant underestimate, our findings suggest. On the first farm, the annual emissions of methane per cow is estimated as 145 kg from the slurry pit, while the figure is 198 kg on the second farm, so 3.8–5.2 times greater. These measurements accord with those found in the Canadian study. If nationally representative, they would suggest that the UK's emissions of methane from slurry storage are broadly equivalent to those calculated from enteric fermentation, a ratio close to 50:50, rather than the 75:25 enteric to manure that is currently reported for dairy cows in the UK National Inventory.

5. Constructing official estimates of methane emissions: the UK example

According to its National Inventory, the UK emits 51.7 Mt CO_2e of methane (assuming a global warming potential of methane over 100 y), which makes up 12% of the UK's total net emissions of 409.5 Mt CO_2e (Department for Energy Security and Net Zero (Department for Energy Security and Net Zero [DESNZ] 2023). The main sources of UK methane emissions are landfill waste sites, leakage from the oil and gas sector, and agricultural emissions. There have been significant reductions in emissions from waste and the oil and gas sectors since the 1990s and total UK methane emissions have fallen by 64% since 1990 (DESNZ 2023, table ES2, p 37). This is a greater reduction than in other OECD countries leading to UK claims to be 'a global leader' in reducing methane emissions. Methane emissions from the energy sector are calculated to have fallen by 84% between 1990 and 2020, for example. This is principally because of the decline in coal power, the reduction in North Sea oil and gas production and reduced leakages from the gas supply system. Emissions from the waste sector have fallen by 75% between 1990 and 2020 by reducing biodegradable waste going to landfill and by more effective collection of methane from landfill sites. Because of these reductions, agriculture is becoming a relatively more prominent source of emissions (Ward 2023). It now accounts for

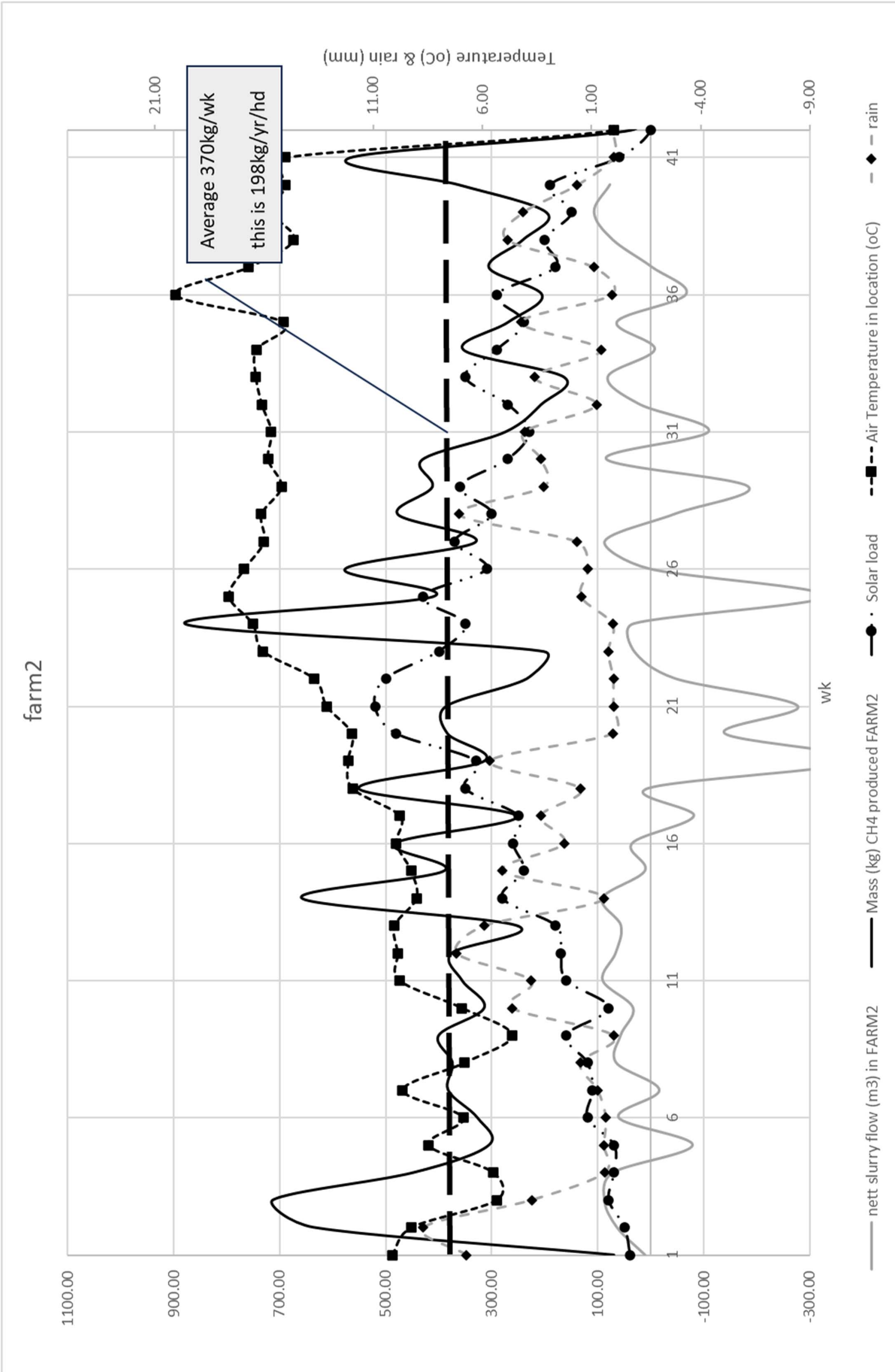

Figure 2. Methane Emissions from Farm 2, Cornwall, England.

Figure 3. A Slurry Storage Facility with an Air-Tight Cover to Capture Methane Emissions.

almost half (48%) of UK's total methane emissions, and methane accounts for over half (54%) of agriculture's emissions (Department for Environment, Food and Rural Affairs [Defra] 2023).

UK agriculture was estimated to have emitted around 25 Mt CO_2e of methane in 2020. Methane emissions from UK agriculture are calculated to have fallen by approximately 15% since 1990, because of a decline in the cattle population in the first two decades of that period. Since 2009, however, methane emissions from agriculture have fluctuated around 25 MtCO_2e and there is no evidence of any declining trend since then (Defra 2023). The UK's most recent National Inventory Report (for 2021) was published in April 2023 (DESNZ 2023). GHG emissions from agriculture are calculated using the UK Greenhouse Gas Inventory Model for the agricultural sector. The modelling forms part of the National Inventory System overseen by the DESNZ and involving Ricardo Energy & Environment as the Inventory Agency and other contributors such as Rothamsted and UK-CEH, both specialist research institutes working on agriculture and the environment. A major research programme was funded between 2011 and 2017 to improve the calculation methodology for agricultural emissions (see, for example, Misselbrook *et al* 2016). The model incorporates analysis of the key underlying variables driving GHG emissions, including soils, climate, livestock and cropping characteristics and farm management practices. It contains a separate module for each of the main agricultural emissions sources and each source has its own source-specific input and output tables. Data are collected and calculations performed by year, since 1990, by the four parts of the UK at a 10×10 km grid resolution, with results then aggregated across the four countries. The UK pursues a Tier 3 approach to enteric emissions from cattle and sheep (i.e highly tailored to specific circumstances within the UK), but a Tier 1 approach to enteric emissions from other livestock. For manure management, it largely pursues a Tier 2 approach except for some minor aspects of emissions from goats, horses and deer.

Enteric emissions for dairy cows and other cattle are estimated using a UK-specific relationship between daily enteric emissions and feed dry matter intake. Cattle are managed according to four regimes—year-round housing, winter housed and summer part-housed (overnight), winter housed and summer grazing, and extended grazing. The proportion of the national herd under each regime is estimated based on a 2014 survey for cattle in England, Scotland and Wales and 2021 research in Northern Ireland (DESNZ 2022, pp 347–8). Different relationships between dry matter intake and emissions are used for lactating and non-lactating cattle.

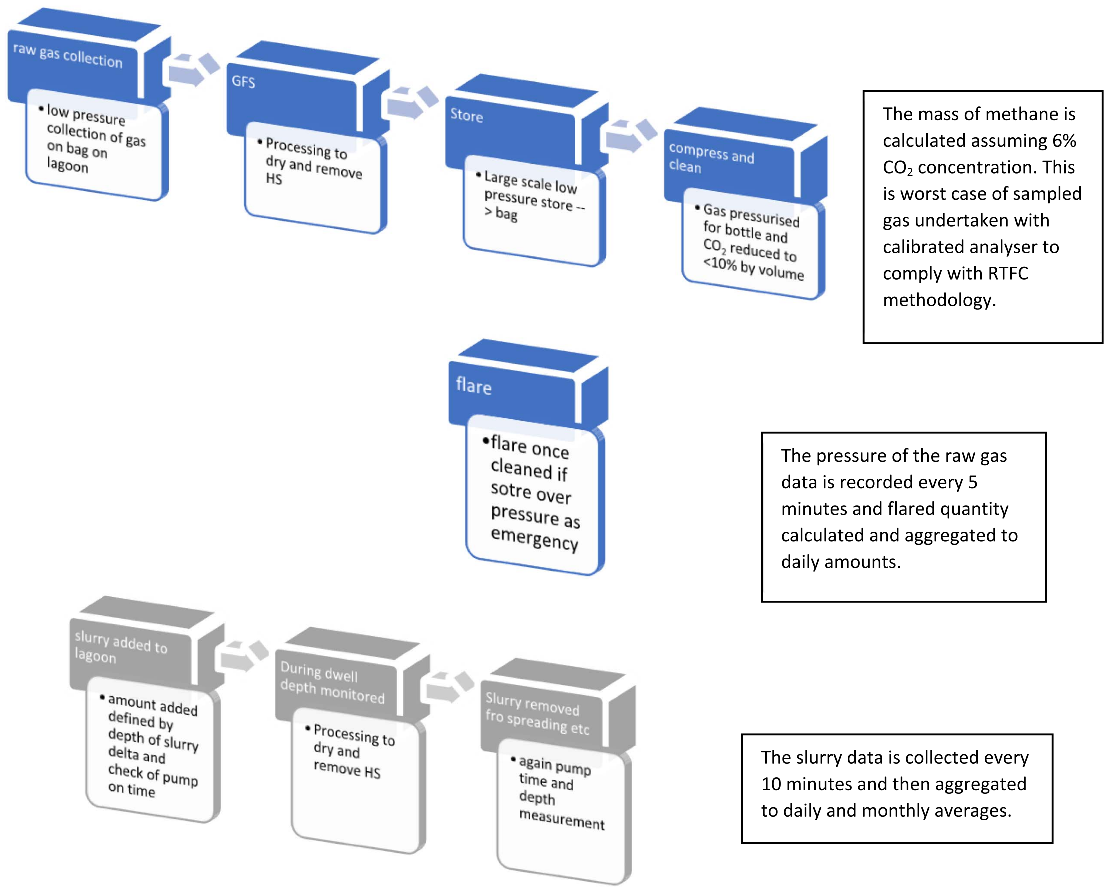

Figure 4. Collecting and Processing Methane from Slurry Storage Facilities.

The data files and calculations for the UK National Inventory Report are published and also available from the UN. Tables in the UK National Inventory show the underpinning assumptions and calculations which generate the overall calculations for methane emissions from enteric fermentation and manure management for different types of livestock. Emission Factors vary between dairy cows (38.26 kg CH_4/head/year) and other cattle (6.9 kg CH_4/head/year) by a factor of over 5 (DESNZ 2023, tables 3.As1 and 3.B(a)s1).

The UK's 2023 National Inventory reports that total enteric methane emissions in 2021 were 841 kt CH_4 across all categories of livestock, while total methane emissions from manure management were 153 kt CH_4 (DESNZ 2023, p 345 & p 355). The 2022 Inventory reported that research trials in the UK found that the methane producing potential of cattle excreta in the UK were not significantly different from IPCC default values. The UK uses the IPCC's default MCF values, which give MCFs under different average annual temperature conditions for different types of manure management (IPCC 2006, table 10.17, p 10.44).

What would the UK national totals for methane emissions from manure management on dairy farms look like if the field measurements we report were used instead of the calculated figures used in the inventory? The average of the two Cornish farms was 171.5 kg per cow in contrast to the 38.26 kg used as the implied emission factor in the inventory. If the Cornish farms were representative of all UK dairy farms with slurry systems, we would estimate that total methane emissions from manure management would be 2.8 times greater and so would be 199 kt of methane rather than the reported 71 kt[9]. This would mean total methane emissions from UK dairy cows (enteric and manure management combined) would be 429 kt rather than the reported 301 kt (that is 42% higher) and manure management would make up 46% of all methane emissions from dairy cows rather than the reported 23%. These calculations, comparing the inventory figures with those based on field measurements, suggest that there is a good case for further research to better understand the pattern of emissions from manure management. Systemic under-reporting of methane from manure management could be distorting priorities for research and for mitigating action.

[9] The UK National Inventory reports that slurry systems cover 61% of dairy cows in the UK.

6. Missed opportunities with methane and manure

The obscuring of methane emissions from manure management compared to enteric fermentation is leading to missed opportunities. Emissions from manure management could be mitigated to reduce the accumulation of GHGs in the atmosphere and slow rates of global warming. There are also economic opportunities to capture methane, process it and use the gas as a fuel source to replace fossil fuels. If methane emissions from manure measurement are four to five times greater than assumed for dairy cows on slurry systems, this only serves to magnify the scale of these two sets of opportunities.

Technology exists to cover slurry storage facilities with air-tight covers and capture the methane emitted from the slurry for processing and use. (Emissions could also be reduced by using acidification, but this would not yield utilisable fuel). Capturing methane from manure management provides a fuel source that can be used on farms or sold to others. Bennamann (2023), a biogas technology company based in Cornwall, have developed a system for capturing and processing methane emitted from slurry storage facilities. The technology includes an airtight cover, combined with a methane liquefaction and storage system. CNH Industrial (Case New Holland) agricultural machinery manufacturers, based in Essex in south east England, have developed a methane-powered tractor which was launched in December 2021 (CNH Industrial 2023). In Bennamann's system, slurry is scraped from farm buildings and yards into a slurry storage facility, which is covered by an airtight impermeable cover. The gas is captured under the cover and removed periodically and treated through a mobile biocycling system and compressed or liquified into a fuel that can be used in vehicles. A Cornwall County Council sponsored scheme has six farms participating in a biogas processing trial. The captured fuel is currently used to power local authority vehicles and it is estimated that 60 vehicles can be fuelled through the scheme. Among other benefits of capturing methane emissions in this way are reduced local air pollution from ammonia emissions and improved slurry management and reduced need for manufactured fertilizers.

If manure management emissions from dairy herds in advanced economies were captured or abated, this would reduce GHG accumulation and increase the prospects of keeping global temperatures within the goals enshrined in the Paris Agreement. In 2017, it was estimated that the median increase in global average temperatures was 0.0179 °C per year (Rahmstorf *et al* 2017). Figure 5 shows the effect of the methane emissions from manure management from the UK and EU dairy herd. The grey dotted line shows the contribution of those emissions calculated using the IPCC methodology. The green line shows the pattern of emissions if a figure of 170 kg per cow per year were used. The gap on the right axis represents the increased contribution of emissions from manure management of UK and EU dairy cows to global warming by 2050. The global warming potential of the gas is therefore time weighted based on the time between the x-axis date and 2050. The x-axis represents years from 2050, and the gradient of the graph's green line helps illustrate the urgency of addressing emissions and also the value of mitigating emissions as soon as possible. The warming potential of these methane emissions from the UK dairy herd is equivalent to the emissions from 347 930 815 000 l of diesel. The total carbon value of those dairy emissions, if the carbon were to be traded, is £31 billion[10]. Capturing the emissions from manure management of the EU dairy herd would represent a saving equivalent to $4.1*10^{12}$ l of diesel, or 5.8% of the remaining global temperature rise budget if temperature were to be kept to 1.5 °C of warming.

7. Conclusions

This study has presented an analysis of the scientific basis for the Tier 2 calculations of methane emissions from manure management. It has reviewed recent studies and presented new data from detailed measurements on two English dairy farms. The findings suggest that there is a good case for further systematic research into methane emissions from manure management under different geographical and environmental conditions. Our findings shed new light on the question of the relationship between methane emissions from manure management and ambient air temperature. It seems plausible from field measurements that emissions are four to five times higher than previously assumed. A shift of this scale would put manure management broadly on a par with enteric fermentation as a source of methane emissions in the dairy sector. Moreover, the technology exists for capturing, processing and utilising the methane that is currently lost to the atmosphere and contributing to GHG accumulation and looks economically promising if an incentives framework for capital investment on farms, coupled with regulatory-forcing, can be devised. The cumulative contribution of methane from dairy farm manure management is significant and there are considerable benefits from acting sooner rather than later to curb emissions. As well as the justification in

[10] This estimate is based on a calculation of £100 per tonne of carbon.

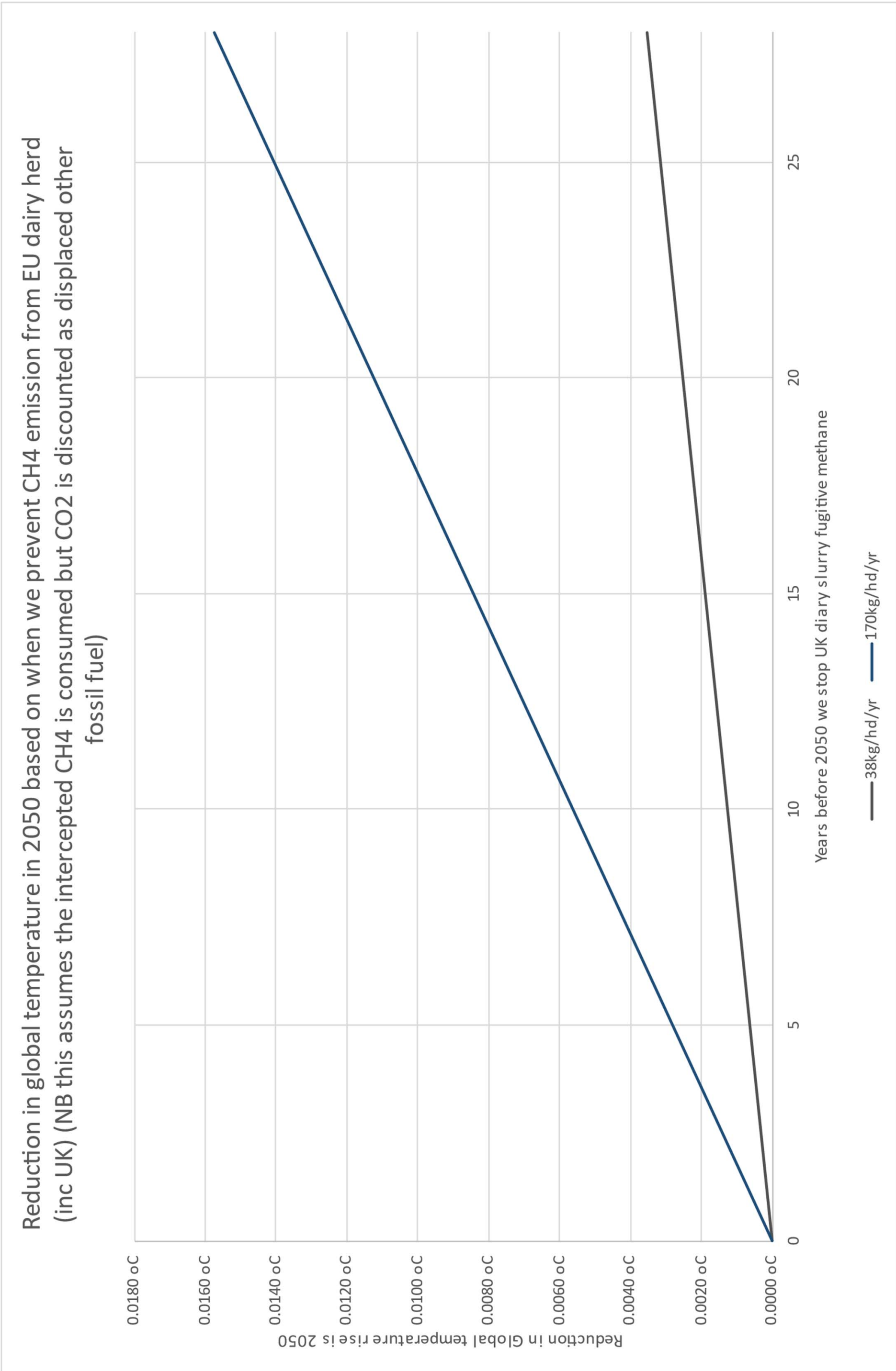

Figure 5. Global Temperature Rise Averted by Capturing Methane Emissions from the UK and EU Dairy Herd.

terms of reduced GHG emissions in the short term, the realisable economic value of this alternative fuel source would be a welcome contribution to the increasingly challenging farm business economics in the dairy sector. Research should therefore also focus on the obstacles and barriers to adopting these technologies and how they might best be overcome.

Despite evidence in the scientific literature of emissions from manure management at levels considerably higher than calculations presented in national inventories would suggest, we found a relatively high level of espoused confidence in the policy community around the elaborate calculation system, perhaps in part because of its complexity and seeming sophistication. However, if emissions from manure management are being significantly under-estimated, this not only means that official estimates are inaccurate, but also that priorities around mitigation options might be being distorted. This paper therefore represents an urgent call for further work to better understand methane emissions from manure management which is surely a suitable case for treatment.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: www.ifeaa.com/.

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Ethical statement

The research for this paper did not directly involve human or animal subjects.

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