The potential of feed additives to improve the environmental impact of European livestock farming: A multi-issue analysis.

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The potential of feed additives to improve the environmental impact of livestock farming: A multi-issue meta analysis.

Abstract

The purpose of this study was to conduct a comprehensive systematic review to identify feed additives, listed on Annex 1 of the European Union Register of Feed Additives, that have potential to reduce polluting emissions from livestock and to conduct a very simple meta-analysis of the collated data in order to identity the potential efficacy of these substances and agents. This study differs from the many other meta-analyses published in this general area in that it encompasses a broader range of environmental impacts and animal species within a single study than has occurred heretofore. The review identified 37 substances and agents offering benefits for six different potentially polluting emissions: gaseous releases of ammonia, methane, carbon dioxide, odours and excretion of nitrogen and phosphorus for four animal groups: cattle, sheep, pigs and poultry. The meta-analysis showed that very considerable reductions in these emissions may be achievable, particularly in respect to ammonia and greenhouse gases. Estimates based on modest levels of usage in the European Union suggest that a reduction greater than 168 kt ammonia and 7100 kt methane could be achievable. However, in order to maximise these benefits regulators and the wider-industry need to implement policies, processes and incentives to encourage greater uptake.

Keywords: *livestock farming; feed additives; sustainable agriculture; environmental impact; greenhouse gases; ammonia*

Introduction

Whilst society relies heavily on livestock farming for a wide variety of goods, for example meat, dairy produce, leather and wool, and services such as rural employment and countryside management, the industry is responsible for a range of well documented environmental impacts. According to the well-cited report 'Livestock's long shadow' (FAO 2006) animal production represents a significant source of the greenhouse gas (GHG) methane amounting to around 18% of global anthropogenic greenhouse gas emissions and around 37% of the total anthropogenic methane releases. Livestock farming is also a major source of malodorous gaseous emissions such as ammonia and hydrogen sulphide. Ammonia can be produced in large quantities from animal excreta, for example, from manure and slurry stores, and livestock buildings and is a particular problem for intensive pigs and poultry enterprises. Statistics for the EU-27 reports that 3364 kt of ammonia was produced by agriculture in 2010 (Eurostat 2012a). Ammonia deposition to land or water can cause eutrophication and acidification of natural ecosystems, and may increase the risk of acid rain deposition (Fangmeier *et al*. 1994). Phosphorus pollution from manures and slurries can also trigger aquatic eutrophication and exacerbate the overgrowth of algae in surface water including certain harmful cyanobacterial algal blooms that are potentially a serious health hazard for humans and animals (Kotak *et al*., 1993). Although nitrate leaching is greater from arable farms, livestock manures and slurries also contribute towards the problem (e.g. Shepherd and Newell-Price 2013, Hansen *et al*. 2012).

Whilst this could be viewed as quite a concern, many farmers, and quite possibly the majority, take these issues seriously and try to manage their land and livestock in an environmentally responsible manner. Nevertheless, it is recognized that more needs to be done to reduce emissions. In addition, there is a general trend towards 'greening' European policies to minimise environmental impact particularly with respect to the need to address climate change. For example, there is an ongoing process of mainstreaming climate change objectives into the European Union Common Agriculture and Water Policies (Medarova-Bergstrom *et al*. 2011, Brouwer *et al*. 2013). Therefore all possible options for environmental improvements need to be examined and so both farmers and regulators are looking towards science and technology to further the cause. There are many possibilities. For example, anaerobic digestion of farm slurries will produce a methane-rich biogas that can be captured and used for electricity or heat generation although it does have the disadvantage of requiring a high capital outlay. Making full use of improving genetic resources for improved animal efficiency is another option. The use of urease inhibitors will result in less ammonia volatilization and nitrification inhibitors can be used to reduce the biological oxidations of ammoniacal-nitrogen to nitrate-nitrogen (Zaman *et al*. 2013, Soares *et al*. 2012).

Another potential approach is the manipulation of livestock diets. Feed intake and feed type can be adjusted in order to alter ruminal microflora which can significantly influence methane emissions from cattle (Johnson and Johnson 1995). Reducing dietary crude protein may also reduce ammonia emissions from livestock excreta (Hayes *et al.* 2004). Taking this a step further, research has also been undertaken to explore the potential of diet supplementation to deliver environmental benefits (FAO 2011). Certain substances added to livestock feeds (i.e. feed additives) can be used to improve animal digestive processes such that nutrients are used more efficiently leading to a reduction in waste production. In turn this may reduce nitrogen and phosphorus lost in excreta as well as reducing methane, ammonia and other noxious metabolic gases. Therefore, some feed additives could have an important role to play in delivering sustainable increases in productivity coupled with simultaneous reductions in damaging pollutants.

Feed additives have been used in livestock production for a long time. Indeed, supplements such as urea and antibiotics were one of the factors attributed to the huge increases in livestock productivity seen in between 1940 and 1960 (Summons 1968). Today it is a huge industry and according to one market report, the sector will be worth over $18billion globally by 2018 (Watt Global Media 2013). Reports vary but North America and Asia-Pacific are heavy users and emerging countries such as China and Brazil have a rapidly increasing share of the market. However, European livestock production is also a significant user, particularly the pig and poultry sectors, and, according to one market report, had 35% of the market share in 2011 and this is growing driven by the rise in meat consumption, concerns regarding meat quality and safety, and various livestock disease worries (Watt Global Media 2013). Whilst the use of feed additives is widespread, it is currently driven wholly by desires for increased productivity and improved animal health and not by their potential to deliver environmental benefits.

Many researchers have explored the potential of feed additives in respect of their effect on polluting emissions both directly (e.g. Beauchemin and McGinn 2006, McGinn *et al*. 2004), and indirectly as a consequence of studying a substances effect on livestock performance. For example, ammonia is measured in many studies investigating the effect a feed additive has on performance (e.g. den Brok *et al*. 1999) and the phosphorous content of excreta and urine is often measured in trials investigating the effect that the phytase enzyme has on pig performance (e.g. Brady *et al*. 2002). Whilst there is no paucity of research in this area, the majority of livestock trials and published reviews consider just one parameter, for example, methane, ammonia or nitrogen (e.g. McGinn *et al*. 2004, McCory *et al*. 2001). Where multiple parameters are measured they tend to focus on just one aspect e.g. metabolic gases or excreta composition or are limited to a specific group of substances such as the organic acids, antibiotics or tannins (e.g. Jayanegara *et al*. 2012, Murphy *et al*. 2011, Tedeschi *et al*. 2003). Little has been done to consider this highly valuable data collectively to more broadly evaluate the potential for feed additives to reduce the environmental impact of livestock farming. Another issue is that environmental relevant emissions are highly variable and affected by many elements such as health, nutrition, genetics, reproduction, and behaviour and so the data from a single study may not provide insightful into the real potential of feed additives. Such a holistic approach would be required to, for example, establish the need to develop policy or regulatory processes to support the use of feed additives for this purpose, and to encourage manufacturers to explore the potential of additives in this respect and promote these benefits to farmers to encourage uptake.

If feed additives are to be used to reduce potentially damaging emissions from livestock there is a need to ensure that in the process of reducing one pollutant there is not a deleterious increase in any others. It is also possible that some feed additives offer benefits in multiple areas and unless a more rounded and holistic evaluation is undertaken these win-win substances could be overlooked. What is, therefore, needed is a secondary analysis of the original data (i.e. a meta-analysis) whereby an attempt is made to combine the findings of individual studies to provide greater insight into the issue (Glass 1976, Nordmann *et al*. 2012). Meta-analysis is widely used in evidence-based research especially for clinical applications (e.g. Gross *et al*. 2013, Delewi *et al*. 2013) and for policy development (e.g. Scheper *et al*. 2013; Mantyka-pringle *et al*. 2012). Such an approach helps to overcome the limitation of small sample sizes and non-representative outcomes by pooling results from a number of individual studies to generate a best estimate. There have been a number of studies that have taken a meta-analysis type approach to assess collectively the results of multiple feed additive trials, but these have still tended to be highly focused. For example, Ungerfeld *et al.* (2007) used meta-analysis to better understand the effects of fumarate addition on ruminal methane production and Jayanegara *et al*. (2012) used a meta-analysis to evaluate the relationship between dietary tannin and methane production in ruminants.

The purpose of this study was to conduct a comprehensive systematic review and a simple meta-analysis of the collated data in order to identity the type and range of substances that, when used as feed additives, could deliver reductions in polluting emissions from livestock and to also consider how significant these environmental benefits might be.

Methods

The study boundaries were constrained to farm-animal trial data published post-1990 and restricted to only those studies where direct environmental effects were measured. Consequently, this excluded studies with companion, zoo and wild animals, and also those that were dietary manipulation rather than supplementation. Studies with fish were also excluded. It also meant that studies using Life Cycle Analysis, mechanistic and metabolic modelling approaches were omitted as well as those where environmental benefits were related to performance improvements alone i.e. by seeking to improve productivity which then reduces production emissions when presented as a function of productivity e.g. g kg^{-1} BW or g kg^{-1} milk.

Initial evaluation

Scientific papers, research and industry reports, and other literature were sourced mainly from on-line databases supplemented by manual searching of key journals and provision of information directly from industry. In addition, reference ‘snowballing’ was used, whereby the cited references in each publication are utilised as a rich source of other related works. Once relevancy checks had been conducted and duplicates had been removed a 'pool' of 461 scientific studies had been identified. Each of these was compared against a comprehensive set of ‘Inclusion Criteria’ established to assess relevance and fitness-for-purpose with respect to the study and, in particular, to ensure that the data used was original, statistically sound and that all the required data had been reported adequately (Lewis *et al.* 2013).

After this evaluation, 270 documents remained and from these 302 individual studies were evaluated covering 246 substances and agents used as feed additives. Of these 246 substances and agents 96 were listed in Annex 1 of Edition 165 of the European Union Register of Feed Additives (EU 2013) being approved for use under EU regulation 1831/2003, albeit approval not necessarily being granted for the same animal species or same functional group (e.g. technological, sensory, nutritional etc.) as that studied. This regulation ensures that only substances that have successfully negotiated a rigorous evaluation process will be granted approval to be placed on the European market. Results herein are focused on Annex 1 substances as these have already passed the rigorous regulatory evaluation processes and, although a new authorisation for use as a zootechnical additive would probably be required if they were to be marketed in the EC in terms of their environmental benefits, they have greater potential to be made available for this new purpose relatively quickly compared with those that have no prior authorisation history. And, indeed, if the substance is already being used as a feed additive and providing dose rates are appropriate the environmental effects identified will be realised regardless of the primary purpose the additive is being used for.

Meta analysis and study limitations

For each of the relevant studies data related to experimental conditions and environmental parameters were extracted into a database in preparation for the meta-analysis. The general procedures described by Eggerm (1997) were used for the analysis. The challenge that any meta-analysis must overcome is that it needs to find a way of combining seemingly disparate studies. Those considered in this analysis varied in many ways even when data was organised initially on the basis of the feed additive, *in vivo* / *in vitro* approaches, animal type and environmental parameter. For example, research has shown that the level of the environmental effect is directly related to the livestock diet (e.g. De Oliveira *et al*. 2007, Machmuller *et al*. 2001) and the diets varied enormously from one study to the next, offering no consistency. In addition, the results of the studies were presented in a wide variety of different metrics and study findings will often vary depending upon the metrics used. For example, consider ruminal methane production, an effect might not be seen when the data is presented as g day^{-1} but might be evident on the basis of g kg^{-1} BW or g DM I^{-1} (dry matter intake). This is illustrated by a study reported by Woodward *et al*. (2006) who considered the effect of various sunflower and fish oil mixtures had on ruminal methane production. One particular mixture showed that, compared to a negative control and measured as g CH_4 day^{-1}, methane production decreased by 5.7%. However, when reported as a function of production (i.e. g CH_4 kg^{-1} milk) methane emissions decreased by 10.9%.

This was not an ideal situation. However, the main objective of this study was simply a screening exercise in order to provide a general picture of the range of substances and agents which when used as feed additives may have potential to reduce polluting emissions. A means of demonstrating the range and scope of effects identified was required even if a more precise picture of the potential environmental effect was less easy to quantify. This was achieved by using a metric-free approach such that data was converted to a % change value (%Δ) i.e. the change in environmental parameter compared to a negative control. Due to the potentially significant differences between the studies with respect to methods and metrics only substances and agents where a %Δ <-10 (i.e. decreases in emissions of more that 10%) were considered to have effectively demonstrated potential for beneficial effects and, likewise only those where a %Δ >=10 (i.e. an increase in emissions of equal to or more than 10%) were considered to have effectively demonstrated potential for a deleterious effect.

Results

Environmental benefits were not identified for all of the 244 substances examined; only 128 were positive in this respect and, of these, only 37 were listed on Annex 1 of the European Union Register of Feed Additives (EU 2013). The studies considered in this review covered cattle (including buffalo), sheep (including goats), pigs and poultry. Data for six different environmental effects were identified (i.e. methane, ammonia, carbon dioxide, odour and excretion of nitrogen and phosphorus) although not all environmental effects were observed in all animal groups. The review findings are presented in Tables 1 to 4 for cattle, sheep, pigs and poultry respectively and arranged according to very broad substance groups. The full data set is given in Lewis *et al.* (2013) and its annexes along with further details on how the data set was prepared and full bibliographical details for each study used. The negative values displayed in these tables identifies a mean potential reduction in the emission (across all studies) whilst a positive number identifies an increase in emissions. The data in parentheses is the number of studies used to identify the best estimate and the range of %Δ values i.e. the maximum and minimum values seen across all studies included in the review. The data for nitrogen and phosphorus excretion is a combination of that reported as both excretion and retention, making the assumption that these are equivalent.

Twenty-five different substances and agents were found to affect polluting emissions from cattle (Table 1) and these are predominately for methane and ammonia. These substances were, in the majority, botanical extracts (e.g. essential oils, spices, vegetable oils, tannins and saponins) and offer mean potential reductions of methane up to 71%Δ (cinnamon (*Cinnamomum verum)*) and 47%Δ ammonia (tannic acid). For some substances benefits are seen for more than one pollutant simultaneously. For example, cinnamon, oregano (*Origanum vulgare)* extract, thymol and clove oil (S*yzygium aromaticum*) all appear to simultaneous reduce both methane and ammonia. These win-win substances could be potentially very valuable. It should however be noted that in many cases these observations were made on very few studies and consequently more research is desirable to confirm these observations and prove their efficacy in this respect.

The effects seen are not always positive, particularly with respect to ammonia emissions and four substances (malic acid, guava (*Psidium guajava),* linseed oil and sunflower oil) are shown to increase ammonia whilst decreasing methane. This obviously significantly reduces the potential benefit of that substance with respect to environmental protection. Mitigating one environmental effect at the expense of another is not desirable. Beneficial effects on nitrogen excretion was also reported by Mwenya *et al*. (2005) who used the α-amino acid L-Cysteine (-20%Δ, albeit just one study) and by many authors (including Benchaar *et al*. 2006, Budan *et al.* 2013) who used the ionophore antibiotic monensin sodium (-13%Δ).

There are several substances that appear to reduce carbon dioxide emissions. Carbon dioxide is rarely cited as an issue with respect to the contribution ruminants make towards global greenhouse gases (GHG). Carbon dioxide from livestock respiration has been estimated as accounting for 21% of anthropogenic GHGs worldwide Worldwatch (2009). However, the FAO (2006) excludes livestock respiration from its global estimate of GHGs arising from livestock agriculture as it considers that it is not a net source of carbon dioxide as it is part of a rapidly cycling biological system, where the plant matter consumed was itself created through the conversion of atmospheric carbon dioxide into organic compounds (Hamilton *et al*. 2007). Since the emitted and absorbed quantities are considered to be equivalent, livestock respiration is not included. Worldwatch (2009) consider this argument flawed and present a convincing argument on several fronts including suggesting that classing livestock as a 'carbon sink' is misleading and that, in reality, livestock are an anthropogenic convenience and so their carbon dioxide emissions should be included in any estimates. Indeed, it does seem appropriate and logical that any opportunity for reducing carbon dioxide should be considered. Nevertheless carbon dioxide arising from livestock respiration appears to receive little attention and it was not evaluated in any of the studies as the primary objective (with the exception of Hamilton *et al*. 2007) but was in some instances one of the parameters measured during the analysis of respiratory gases, particularly in open-circuit respiration studies. In this review several substances were found to reduce carbon dioxide emissions, for example cinnamon offered reductions of 42%Δ, garlic oil showed similar decreases of 40%Δ and both common Juniper (*Juniperus communis)* berry oil and coconut (*cocos nucifera*) oil also induced reductions albeit at a less significant level. However, due to the lack of data for this parameter it is unlikely that the results herein are representative of the true benefits of feed additives in reducing carbon dioxide.

No sound evidence was identified to show that substances and agents used as cattle feed additives could reduce odours or the emissions of malodorous compounds.

The effects seen for sheep and goats (Table 2) are largely similar to those seen for cattle. Again botanical extracts dominate amongst the potentially 21 valuable substances identified and many of these substances are the same as those producing benefits in cattle. Reductions in methane emissions appear potentially very significant. For example, a study reported by Garcia-Gonzales *et al.* (2008) showed mean reductions of 75%Δ with root extracts from rhubarb (*Rheum officinale)* and Sallam *et al*. (2009) showed that *Eucalyptus oil* could reduce methane emissions of 60%Δ. Benefits for ammonia are also quite significant with, for example, thymol and clove oil both demonstrated mean reductions of 46%Δ. Again many substances are shown to deliver simultaneous benefits for both methane and ammonia however there were no data for carbon dioxide emissions and no benefits for either nitrogen excretion or odours were identified in the literature. Unlike the studies with cattle, none of the substances considered appeared to increase ammonia emissions.

The studies conducted with pigs (Table 3) identified just five substances and agents offering environmental benefits and, with the exception of fumaric acid, these were different to those identified for the ruminants. Based on the studies herein, the carboxylic acids all appear to reduce ammonia emissions, with the greatest potential shown by benzoic and adipic acids at 23%Δ and 25%Δ respectively. However, a recent assessment of benzoic acid by the European Food Safety Authority (EFSA) regarding its efficacy in reducing ammonia emission from pig manure was inconclusive due to insufficient data (EFSA, 2012a). Nevertheless two of the studies evaluated did demonstrate significant reductions at a dose rate of 10,000 mg kg^{-1}. Reductions seen by fumaric acid appear less significant than those for benzoic and adipic acids at 12%Δ. The enzyme phytase is well studied (e.g. Emiola *et al*. 2009, Smith *et al*. 2004, Levic *et al*. 2006) and documented according its ability to reduce phosphorus excretion and the studies considered in this review showed that reductions of around 21%Δ may be feasible. One study (Smith *et al*. 2004) showed that this effect may be accompanied by a simultaneous reduction in ammonia emissions. A study reported by Armstrong *et al*. (2000) showed that using cupric sulphate may reduce odour from pigs by around 11%Δ but no evidence that any of the other substances and agents considered herein had potential for odour reductions was identified.

The study did not identify a great deal of convincing evidence of significant environmental benefits achievable via the use of feed additives (at least not those already on Annex 1 of the EU feed additives register) with poultry (Table 4). Just three substances and agents were identified. Only bentonite was identified with potential to reduce ammonia (41%Δ). Bentonite is currently authorised as binder, anticaking and anticoagulant agent in feed additives (EFSA 2013, 2012b). The other two substances/agents did demonstrate an effect on phosphorus excretion; the enzyme phytase reduced it by 28%Δ and citric acid by 16%Δ.

Discussion

From the results presented in Tables 1 to 4, even considering all the caveats regarding data variability, a limited number of studies in some instances and disparities in study approaches and presentation, it is evident that some substances and agents may offer very significant opportunities to mitigate polluting emissions and, if realized, would contribute to making this sector more sustainable.

Modelling and calculating potential reductions in emissions and environmental impacts is a complex discipline that is often highly dependent on spatial factors. Thus attempting to provide an assessment of potential impacts on a European scale was not very feasible within this short study. However, some very basic calculations have been made based on national and European inventories in order to place the potential impact in to context.

In Europe, about 95% of ammonia emissions arise from agricultural sources, with the main contributions arising from livestock housing (~43%), manure handling (~26%) and mineral fertilisers (~26%) (Eurostat 2012a, Skjøth and Hertel 2013). As mentioned above agriculture accounts for 3364 kt of ammonia (Eurostat 2012a) and up to 73% (i.e. 43 + 26 / 95 * 100) of this comes from livestock sources, accounting for 2456 kt. Based on data from the EU-15 and assuming this is broadly the same for the EU-27 (EC & EEA 2012) about 78% comes from cattle, 15% from pigs, 5% from poultry and 1% from sheep, corresponding to 1915 kt for cattle, 368 kt for pigs, 123 kt for poultry and 25 kt for sheep. Table 5 below shows the range of potential emissions reductions that might be possible with the feed additives reviewed herein (only including additives that have emission reduction benefits).

Table 5 shows that ammonia emissions could potentially be reduced by up to 30% using feed additives. This is based on a 100% uptake and the assumption that feed additives will reduce all sources of ammonia emissions from livestock. However, even if these assumptions are taken into account, i.e. emissions reductions are lower and there is lower uptake, e.g. 20-30%, the potential emission reductions could be significant, especially for cattle. For example, a 20% uptake for cattle could result in a 5% emission reduction (168 kt NH_3), which is significant given that during a twenty year period (1990-2010) ammonia emissions only reduced by 30% (Eurostat 2012a).

With regard to methane (CH_4), the agriculture sector produced 461 567 kt of CO_2 equivalent of non-CO_2 greenhouse gases in 2010 (i.e. CH_4 and N_2O) (Eurostat 2012b) contributing around 10% of the total EU GHG emissions. About 42% (195314 kt) of this is methane arising from livestock enteric fermentation and manure management, thus 4.2% of total EU emissions arise from this source. 148123kt (76%) of methane emissions is from livestock enteric fermentation and 47191 kt (24%) is from manure management. Based on data from the EU-15 (EC & EEA 2012) about 86% of enteric fermentation and 52% of manure methane comes from cattle, 2.5% of enteric fermentation and 47% of manure methane comes from pigs, and 12% of enteric fermentation and 1.4% of manure methane comes from sheep, which corresponds to 151925 kt for cattle, 25883 kt for pigs, and 18435 kt for sheep (methane emissions from poultry are negligible). Table 6 below shows the range of potential methane emissions reductions that might be possible with the feed additives reviewed herein (only including additives that have emission reduction benefits. Note: no additives reduced methane from pigs).

Table 6 shows that methane emissions could be reduced by up to 26% using feed additives. This is also based on a 100% uptake and the assumption that feed additives will reduce all sources of methane emissions from livestock. Even at lower uptake rates, e.g. 20-30%, the potential emission reductions could be significant, especially for cattle. For example, the 20% uptake for cattle that was used in the ammonia example above, could result in a 4.6% methane emission reduction (7110 kt CH_4) which may be achieved relatively quickly in comparison to the 20% reduction that was achieved over a twenty year period from 1990 to 2010 (Eurostat 2012b). Even if reductions are only achieved for the enteric fermentation source, a 4.6% reduction would result in 5890 kt (1.3%) reduction in methane emissions.

The agricultural industry urgently needs to identify practical, cost-effective greenhouse gas mitigation measures which can help the sector contribute to challenging emission reduction targets (EC 2012). Whilst many of the feed additives identified herein undoubtedly have mitigation potential and would be simple enough to introduce into livestock feed rations, there is no current direct economic incentive for livestock farmers to adopt practices or technologies that might reduce polluting emissions that arise directly from the animal. Consequently, it is difficult to see why a livestock farmer would invest in feed additives (some of which are expensive) that just reduce emissions unless they also offer other benefits such increased performance and productivity which off-set the cost of the adoption. The main reason why EU approved substances were the focus herein is that their efficacy with respect to other benefits has already been established (e.g. productivity increases, improved health, feed efficiency etc.). However, in order to maximise potential of these substances and agents incentives to encourage their use may still be required. There may be opportunities for policy makers and the industry itself to provide such incentives via, for example, the introduction of specific operations associated with certain feed additives within the environmental stewardship schemes of the European Rural Development Programme or by encouraging assurance and food labelling schemes, both those specific to environmental concerns such as the UK's LEAF Marque (LEAF 2013) or the worldwide meat and poultry schemes within GLOBALG.A.P (GlobalGap 2013), to promote the use of feed additives.

On the broader topic of improving agriculture sustainability, it should be remembered that this perspective of feed additives and their potential for reducing emissions is one small part of the bigger picture. Their use within the whole food production and supply chain needs to be considered and this includes many aspects outside of the boundaries of this study. On the positive side is the valuable role they play in improving animal health, welfare, production and performance. On the negative side there are the environmental impacts caused by, for example, their production, transport, packaging and marketing. So even if there is little evidence that the feed additive may directly reduce polluting emissions from the animal the wider picture should be considered. To illustrate this, this study found no evidence that the amino acid methionine could reduce ruminant metabolic gaseous emissions directly. However, a life cycle assessment (LCA) of its production and use as a feed additive concluded that it can significantly improve the efficiency of production and could reduce the demand for feed raw materials. The report quotes that worldwide use of 750,000 metric tons of methionine could save around 15 million hectares of crop land (ICCA 2009). Similar work is currently being undertaken by the International Feed Industry Federation (IFIF) in their multi-national project to consider the role of speciality feed ingredients in reducing the environmental impact of livestock using an LCA approach to evaluate various enzymes and amino acids (IFIF nd.).

Undoubtedly one of the key challenges of the twenty-first century will be ensuring a positive and proactive response to reducing the environmental impact of farming and, perhaps, in particular the need to reduce atmospheric concentrations of GHG’s. However, this objective needs to be met simultaneously with the equally pressing food security objective, and both are exacerbated by population growth and a global shift towards greater consumption of livestock products (FAO 2011), thus increasing pressure on the livestock industry. So whilst this study only provided a simple assessment of the true potential of feed additives to reduce polluting emissions it does clearly demonstrate that there is a sound case to be optimistic but action is required by policy makers, regulators and the industry itself to encourage uptake.

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Table 1. The potential for feed additives to reduce environmental emissions: Cattle and buffalo studies.

Note: the data in the brackets refers to the number of studies considered and the full dta range seen.

Additive	Ammonia	Carbon dioxide	Methane	Nitrogen (excretion)
Carboxylic acids & their salts, amino acids and fatty acids				
L-cysteine	6 (1; no range)	0 (0)	-4 (1; no range)	-20 (1; no range)
Linoleic acid	0 (0)	0 (0)	-56 (3;-20 to -83)	0 (0)
DL-Malic acid & disodium salt	16 (5;+68 to -6)	0 (0)	-23 (5;neg to -85)	0 (0)
Fumaric acid	0 (0)	0 (0)	-17 (3; -9 to -27)	0 (0)
Antibiotic drugs: Ionophores				
Monensin sodium	-4 (15; +97 to -85)	-7 (2; neg to -14)	-21 (16; +7 to -83)	-13 (2; neg to -26)
Salinomycin	-18 (1; no range)	0 (0)	0 (0)	0 (0)
Plant extracts: essential oils & spices				
Cinnamomum verum	-14 (2;+8 to -50)	-42 (1; no range)	-71 (1; no range)	0 (0)
Allium arenarium oil	-4 (9;+13 to -55)	-40 (1;-36 to -44)	-46 (5;-10 to -91)	0 (0)
Juniperus communis berry oil	-8 (1; no range)	-18 (1; no range)	-49 (1; no range)	0 (0)
Origanum vulgare	-23 (3; neg to -5 to -62)	0 (0)	-50 (1;-13 to -87)	0 (0)

Thymol	-11 (2;+20 to -57)	0 (0)	-41 (1;+12 to -94)	0 (0)
Armoracia rusticana extract	-10 (2;-3 to -19)	0 (1; no range)	-36 (2;-19 to -90)	0 (0)
Syzygium aromaticum	-17 (3;+10 to -54)	0 (0)	-23 (1;-11 to -35)	0 (0)
Mentha piperita oil	4 (3;+19 to -17)	0 (0)	-32 (2;-8 to -76)	0 (0)
Capsicum oleoresin	-27 (5;neg to -90)	0 (0)	0 (0)	0 (0)
Cinnamaldehyde	-16 (5;-4 to -68)	0 (0)	0 (0)	0 (0)
Fenugreek	-4 (2; +16 to -40)	0 (0)	-12 (1; no range)	0 (0)
Plant extracts: saponins & tannins				
Quillaja saponaria extract	-13 (9;neg to -78)	6 (2;+28 to -4)	-1 (8;neg to -12)	0 (0)
Tannic acid	-47 (1; no range)	0 (0)	0 (0)	0 (0)
Terminalia chebula	0 (0)	0 (0)	-38 (1;-29 to -48)	0 (0)
Condensed tannins[1]	-3 (3;+13 to -15)	0 (0)	-19 (7;neg to -40)	0 (1; no range)
Psidium guajava	12 (1; no range)	0 (0)	-18 (1; no range)	0 (0)
Plant extracts: vegetable oils				
Coconut oil	-6 (5;+23 to -60)	-12 (1; no range)	-26 (8;-8 to -100)	0 (0)
Linseed oil	28 (3; +71 to -24)	0 (0)	-28 (2; -12 to -64)	0 (0)

Sunflower oil	46 (1; no range)	0 (0)	-18 (3;-10 to -22)	0 (0)

Notes:
1: Condensed tannins have been listed separately as in these studies the exact botanical source was not specified
2. References for all studies can be found at Lewis *et al.* (2013). Omitted due to space limitations.
Neg = Negligible

Table 2. The potential for feed additives to reduce environmental emissions: Sheep and goat studies.

Note: the data in the brackets refers to the number of studies considered and the full dta range seen.

Additive	Ammonia	Methane	Nitrogen (excretion)
Carboxylic acids & their salts, amino acids and fatty acids			
Linoleic acid	0 (0)	-34 (1;-27 to -42)	0 (0)
DL-Malic acid	0 (0)	-13 (1; no range)	0 (0)
L-cysteine	0 (1; no range)	-13 (1; no range)	0 (0)
Antibiotic drugs: Ionophores			
Monensin sodium	-16 (2;-14 to -19)	-32 (4;+11 to -75)	0 (0)
Plant extracts: essential oils & spice			
Thymol	-46 (1;-19 to -72)	-53 (1;-7 to -99)	0 (0)
Eucalyptus oil	-22 (1;-14 to -30)	-60 (1;-30 to -90)	0 (0)
Thymus vulgaris	-27 (1;+6 to -60)	-48 (1;-3 to -94)	0 (0)
Origanum vulgare	-22 (2;+6 to -68)	-50 (1;-3 to -97)	0 (0)
Cinnamaldehyde	-23 (2;neg to -65)	-48 (1;-3 to -94)	0 (0)
Syzygium aromaticum	-46 (1; no range)	-24 (1; no range)	0 (0)
Anethum graveolens oil	-24 (1;-3 to -50)	-42 (1;-8 to -76)	0 (0)
Cinnamomum verum	-32 (2;-11 to -79)	-26 (2;neg to -98)	0 (0)
Allium arenarium oil	-6 (3;neg to -17)	-24 (4;neg to -74)	0 (0)
Plant extracts: saponins & tannins			

Rheum officinale (root)	0 (0)	-75 (1; no range)	0 (0)
Quillaja saponaria extract	-11 (1; no range)	-17 (1; no range)	0 (1; no range)
Terminalia chebula	0 (0)	-23 (1; no range)	0 (0)
Condensed tannins[1,2]	-18 (2;-9 to -44)	-14 (4;+22 to -54)	0 (2; neg)
Rheum nobile extract	0 (0)	-13 (1; no range)	0 (0)
Plant extracts: vegetable oils			
Coconut oil	0 (0)	-38 (2;-26 to -73)	0 (0)
Sunflower oil	0 (0)	-23 (1; no range)	0 (0)
Miscellaneous			
Ethanol[3]	0 (0)	-48 (1; no range)	0 (0)

Notes:

1. In many studies the exact plant source of the condensed tannins was not given and so a more generic additive name was used.
2. This data is somewhat skewed by one study for goats with a %Δ for methane at -44%Δ (Animut *et al.* 2008). With sheep the Δ% for methane is in the 'no effect category.
3. One study for goats.
4. References for all studies can be found at Lewis *et al.* (2013). Omitted due to space limitations.

Neg = Negligible

Table 3. The potential for feed additives to reduce environmental emissions: Pig studies.

Note: the data in the brackets refers to the number of studies considered and the full dta range seen.

Additive	Ammonia	Nitrogen (excretion)	Odour	Phosphorus (excretion)[1]
Carboxylic acids & their salts, amino acids and fatty acids				
Benzoic acid	-23 (6;+116 to -71)	-9 (1; no range)	0 (2; neg)	0 (0)
Adipic acid	-25 (1; no range)	0 (0)	0 (0)	0 (0)
Fumaric acid	-12 (1;+6 to -30)	0 (0)	0 (0)	0 (0)
Miscellaneous				
Phytase[2]	-26 (1; no range)	-7 (8;+13 to -44)	0 (0)	-21 (12;-126 to +38)
Cupric sulphate pentahydrate	0 (0)	0 (0)	-11 (1;-10 to -12)	0 (0)

Notes:
1. Combined retention and excretion studies
2. This is data for 3-phytase, 6-phytase and non-specific phytase combined
3. References for all studies can be found at Lewis *et al.* (2013). Omitted due to space limitations.

Neg = Negligible

Table 4. The potential for feed additives to reduce environmental emissions: Poultry studies.

Note: the data in the brackets refers to the number of studies considered and the full dta range seen.

Additive	Substance type	Ammonia	Phosphorus (excretion)
Bentonite	Mineral salts & complexes	-41 (1;-10 to -41)	0 (0)
Phytase[1]	Bacteria, enzymes & yeasts	0 (0)	-28 (6)
Citric acid	Organic acids & their salts	0 (0)	-16 (1; no range)

Notes:
1. This is data for 3-phytase, 6-phytase and non-specific phytase combined
2. References for all studies can be found at Lewis *et al.* (2013). Omitted due to space limitations.

Table 5. Range of potential ammonia emission reductions

Livestock	Range in potential reduction (%)		Reduction (kilotonnes - kt)		Proportion of total agricultural emissions (%)	
	Low	High	Low	High	Low	High
Cattle	3	47	57	900	-1.7	-26.8
Pigs	12	26	44	96	-1.3	-2.8
Poultry	10	41	12	50	-0.4	-1.5
Sheep	6	46	2	12	0	-0.3
Total	-	-	115	1058	-3.4	-31.4

Table 6. Range of potential methane emission reductions

Livestock	**Range in potential reduction (%)**		**Reduction (kilotonnes - kt)**		**Proportion of total agricultural emissions (%)**	
	Low	**High**	**Low**	**High**	**Low**	**High**
Cattle	1	71	15	107867	-0.3	-23.4
Sheep	13	75	2397	13826	-0.5	-3
Total	-	-	3916	121693	-0.8	-26.4