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ORIGINAL ARTICLE

Evaluating the potential of dietary crude protein manipulation in reducing ammonia emissions from cattle and pig manure: A meta-analysis

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Abstract Dietary manipulation of animal diets by reducing crude protein (CP) intake is a strategic NH_3 abatement option as it reduces the overall nitrogen input at the very beginning of the manure management chain. This study presents a comprehensive meta-analysis of scientific literature on NH_3 reductions following a reduction of CP in cattle and pig diets. Results indicate higher mean NH_3 reductions of 17 ± 6% per %-point CP reduction for cattle as compared to 11 ± 6% for pigs. Variability in NH_3 emission reduction estimates reported for different manure management stages and pig categories did not indicate a significant influence. Statistically significant relationships exist between CP reduction, NH_3 emissions and total ammoniacal nitrogen content in manure for both pigs and cattle, with cattle revealing higher NH_3 reductions and a clearer trend in relationships. This is attributed to the greater attention given to feed optimization in pigs relative to cattle and also due to the specific physiology of ruminants to efficiently recycle nitrogen in situations of low protein intake. The higher NH_3 reductions in cattle highlights the opportunity to extend concepts of feed optimization from pigs and poultry to cattle production systems to further reduce NH_3 emissions from livestock manure. The results presented help to accurately quantify the effects of NH_3 abatement following reduced CP levels in animal diets distinguishing between animal types

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and other physiological factors. This is useful in the development of emission factors associated with reduced CP as an NH_3 abatement option.

Keywords Manure management · Reduced crude protein · Cattle · Pigs · Dietary manipulation · Meta-analysis · Ammonia abatement

Introduction

Livestock is a mainstay of global food supply and the agricultural economy. It accounts for 10–15% of total food calories and a quarter of the dietary protein consumed around the world (FAO 2011). It also contributes to 36% of the value of world agricultural output and is a source of livelihood for around 1.3 billion people (Thornton 2010; FAO 2011). It is one of the fastest growing segments of the agricultural sector, especially in developing countries. With rapid urbanization, rising incomes and the emergence of the middle class, the global demand for livestock products is projected to increase in the coming decades (Gerber et al. 2013). Meeting this demand is an immense challenge for agricultural production, but it also poses a significant threat to the environment.

Numerous studies have highlighted the negative externalities associated with the expanding livestock sector, particularly in terms of ammonia (NH_3) emissions. In 2014, livestock rearing and production contributed two thirds of the total agricultural NH_3 emissions in the 28 member countries of the European Union (EU-28) (UNECE 2016). NH_3 is an air pollutant and is detrimental to human health, as it contributes to the formation of particulate matter in the atmosphere (Malek et al. 2006). Increased NH_3 emissions lead to eutrophication in lakes and rivers and acidification of soils. Additionally NH_3 emissions constitute a loss in nitrogen (N), which could have been a source of fertilizer when applied to the soil (Sutton et al. 2011). Hence, the abatement of NH_3 emissions from livestock rearing and production is imperative.

There are various sources of NH_3 emissions within the livestock sector. Among these sources, the most prominent are the emissions associated with manure management. Emissions from manure management as defined here encompass emissions from animal housing systems, handling and storage of manure, deposition of manure during grazing and also from the application of manure as a fertilizer to soils. These emissions cover almost all of the total livestock NH_3 emissions in the EU-28 (UNECE 2016). A number of policies have been implemented to tackle NH_3 emissions from the agricultural sector including those from manure management in Europe, especially among the countries in the European Union. These policies impose emission ceilings, monitor and review agricultural practices and also recommend usage of best available techniques (BAT) to reduce agricultural emissions. The objectives, structure and implementation of these policies are guided by published literature, underlining their role in the policy making process. As far as emissions from manure management are concerned, various studies have described and quantified the potential of abatement options to reduce NH_3 emissions (Bittman et al. 2014). These studies are valuable in estimating the emission reduction potentials of abatement options and help design strategies aimed at reducing NH_3 emissions.

The manipulation of crude protein (CP) in animal diets is one such abatement technique to reduce NH_3 emissions from manure management. Animal diet manipulation is a strategic abatement option, since it alters the manure characteristics right at the source and reduces overall nitrogen input. Other abatement options reduce emissions at a particular stage, but do not avoid excess nitrogen input. Changing animal diets has an effect on the whole manure management chain, irrespective of which stage the emissions are measured (Chadwick et al. 2011).

CP is generally incorporated in animal diets to ensure animal growth and maintain bodily functions (van Vuuren et al. 2015). N is a basic component of CP and constitutes around 16% of its mass. While a portion of the ingested protein N is used by the animal to produce meat, milk, eggs, body tissues and offspring, a large percentage is excreted as faeces and urine. N in faeces is mainly in the form of organic compounds and is less prone to losses via volatilization as NH_3. Urine on the other hand, contains N in the form of urea which, when exposed to bacterial urease, is easily transformed to NH_3. This has been highlighted in many studies which report that the presence of nitrogenous compounds (primarily as urea in urine) along with a high manure pH are the main factors leading to NH_3 emissions from manure (Lynch et al. 2007; Feilberg and Sommer 2013). The potential of reduced CP in animal diets to decrease both the amount of N and pH of manure has been demonstrated in various studies (Canh et al. 1998; Lynch et al. 2007; Le et al. 2009). Due to concerns of farmers regarding animal productivity and also due to the safety margins implemented by the feeding industries, dietary CP is usually fed in excess of what is required by the animals. This oversupply of CP leads to a greater percentage of N in manure, and a subsequent increase in NH_3 emissions (van Vuuren et al. 2015). Research has shown that it is possible to reduce dietary CP in animal diets without affecting animal performance and health, resulting in lower NH_3 emissions (Hansen et al. 2007; Agle et al. 2010; Arriaga et al. 2010). This has been made possible by carefully matching the diets with the requirements of the animals. In the case of monogastrics such as pigs, exogenous supplementation of essential amino acids also helps in achieving the required intake of essential amino acids while simultaneously reducing protein intake. This supplementation improves N utilization and reduces N excretion, once again resulting in reduced NH_3 emissions (Panetta et al. 2006; Madrid et al. 2013; Montalvo et al. 2013). Acknowledging this potential, Annex IX to the Gothenburg protocol recommends reducing CP in animal diets to abate NH_3 emissions (UNECE 2015). Reduction of CP in animal diets is also mentioned in the recent guidance document on NH_3 abatement as one of the most cost effective and strategic ways to reduce NH_3 emissions (Oenema et al. 2014).

NH_3 emission reductions from dietary manipulation of animal diets have been quantified using measured and reported NH_3 emissions from experimental studies (Oenema et al. 2014; Hou et al. 2015). Although these results are very useful, they suffer from some drawbacks. Firstly, these quantifications are based on studies that measure the impacts of reduced CP on NH_3 emissions for different animal types (e.g., pigs, cattle) and categories (e.g., gilts, barrows, boars, etc.) (Hansen et al. 2007; Le et al. 2009; Arriaga et al. 2010). Furthermore, emission reductions are reported at different stages of the manure management chain (Portejoie et al. 2004; Madrid et al. 2013) and vary in initial and final CP levels from and to which CP is reduced (Portejoie et al. 2004). NH_3 emissions reductions from reduced CP have not been analysed in light of these factors which lends considerable variability to the reported emission reduction estimates. Hence, even though these studies are helpful in understanding NH_3 emission patterns with reduced CP, simply aggregating emission reduction estimates will likely lead to a gross misrepresentation of the overall reduction potential of reduced CP as an NH_3 abatement option. This highlights the need to better quantify the influence of reduced CP on NH_3 emissions, while distinguishing for animal types and also accounting for other factors which may influence NH_3 emissions. Such an analysis has not been conducted in previous literature.

The present study aims to address this research gap by presenting a comprehensive analysis of NH_3 emission reductions from lowering CP content in animal diets. The results discussed here examine the relationship between reduced CP and NH_3 emissions for both cattle and pigs. The results also explore the effect of reduced CP on total ammoniacal nitrogen (TAN) and of the initial and final CP levels on NH_3 emission reductions. Furthermore, the study also analyses the effect of factors such as manure management stages and animal categories on NH_3 emission reductions.

Methodology

Meta-analysis is a technique used to combine the results from several scientific studies (Kim et al. 2012, 2013; Patra 2013). The study presented here uses a meta-analysis to quantify and compare the effect of a reduction in CP on NH_3 emissions for both cattle and pigs. A meta-analysis constitutes the following key elements (Rosenthal 1985; Sauvant et al. 2008): (1) inclusion criteria, (2) literature search and selection of data sources, (3) estimation of effect size, and (4) statistical analysis. These elements were employed in this study and are described below.

Inclusion criteria

Animal husbandry and related human activities are sources of many different pathways of NH_3 fluxes to the atmosphere. In this paper, we focus on the activities that concern the management of cattle and pig manure. Since a reduction of CP content in animal diets affects all phases of the manure management chain, we consider emissions from urine and faeces excreted in animal housing, during their storage, and their application to agricultural soils. Emissions from manure deposited during grazing are not included in this study. Grazing emissions are common in cattle production systems which often include pasturage, but reduced CP as an NH_3 abatement option is not feasible in such cases since it is difficult to ascertain the amount of CP in the diet and set reduction targets as compared to housed animals. Moreover, the NH_3 emissions from grazing animals are relatively lower than housed animals, since urine, the primary source of NH_3 emissions seeps into the soil on contact (Oenema et al. 2014).

Selection of data sources

Google Scholar was used to search the literature for studies pertaining to NH_3 emissions from a reduction of CP in animal diets. The relevant data sources were then chosen in line with selection criteria described in recent studies that focus on emission reductions in manure management (Hou et al. 2015, 2017; Wang et al. 2017). The selection criteria were as follows: (1) the animal type was either cattle or pigs subject to reduced CP in their diets; (2) NH_3 emissions were measured and reported in at least one of the following manure management stages: housing, storage or application; (3) reference treatments included initial and final CP levels along with reference NH_3 fluxes; (4) studies complied with standards related to animal nutrition and experimental design; (5) the articles were peer reviewed and available in English. The selection criteria resulted in a selection of 22 individual studies measuring NH_3 emissions under reduced CP comprising measurements from on-farm and simulated farm settings conducted in Europe or North America. This consisted of eight studies for cattle and 14 for pigs amounting to 67 unique NH_3 measurements. In addition to NH_3 emissions, TAN content of the manure was also extracted from the studies when available. Related information such as study location, emission measurement technique, animal category, feed type and manure characteristics were also compiled and catalogued (see Table S.1 and S.2 in the supplementary information). Differences between studies that could affect NH_3 emission reductions such as measurement of emissions at different manure management stages and across animal categories were identified and their implications on NH_3 emission reductions were investigated. Other possible sources of variability such as differences in manure management systems, the type of protein sources and physiological stage of animals were also considered, despite the fact that a statistical analysis was not possible due to insufficient data. Variation in NH_3 emissions arising from location, animal production systems, measurement techniques etc. can also influence the reported emission reduction estimates. However, this uncertainty in emission reduction estimates cannot be handled with current knowledge since livestock production is complex in nature and varies between countries and production systems (Stewart et al. 2009; Crosson et al. 2011; Loyon et al. 2016). Currently no standard methodology exists to evaluate the quality, representativeness and transitory nature of emission data pertaining to livestock production systems.

Estimation of emission reduction potentials

Effect sizes were represented as NH_3 emission reductions which were estimated using observations from the selected studies. The emission reductions were calculated relative to the NH_3 emissions during reference CP treatments using Eq. (1).

$$E_a = \left(1 - {E_{rcp}}/{E_{ref}}\right) \times 100 \tag{1}$$

where E_a is the NH_3 emission reduction (%); E_{rcp} is the NH_3 emission after reduced CP treatment; E_{ref} is the NH_3 emissions during reference treatment. The units of E_{rcp} and E_{ref} are dependent on the units used in individual measurement studies. A positive value of E_a indicates a decrease in NH_3 emissions. This allowed for a simple normalization of emission measurements in percentage terms, prior to averaging them. Emissions were also expressed in terms of an absolute change in percentage CP. The difference between initial and final CP, both given in percent, is defined as %-point reduction (e.g., a change from a CP content of 16.5 to 15.5% is regarded a reduction of one %-point). Tables 1 and 2 report all the studies that were used to calculate NH_3 emission reductions for both pigs and cattle respectively. The effect of CP changes on TAN reductions was calculated in the same way as for NH_3 emissions when data were available.

Table 1 Impacts of reduced CP in animal diets on NH_3 emissions and TAN content in manure measured at different manure management stages in pig production systems

Study	CP reduction (%-points)	Emissions measured at	NH_3 reduction (%)	TAN reduction (%)
Canh et al. (1998)	2.0	Housing	22	18
	4.0	Housing	40	39
	2.0	Housing	23	25
	2.0	Housing	26	10
	4.0	Housing	49	34
	2.0	Housing	31	27
Hansen et al. (2007)	2.0	Housing	37	–
Hayes et al. (2004)	9.0	Housing	62	–
	6.0	Housing	53	–
	3.0	Housing	29	–
	3.0	Housing	34	–
	6.0	Housing	47	–
	3.0	Housing	20	–
Le et al. (2008)	6.0	Housing	64	41
Le et al. (2009)	3.0	Housing	29	27
Leek et al. (2005)	3.0	Housing	41	7
	6.0	Housing	43	44
	9.0	Housing	74	64
	3.0	Housing	4	40
	6.0	Housing	56	62
	3.0	Housing	55	36
Leek et al. (2007)	2.0	Housing	23	3
	5.0	Housing	50	31
	8.0	Housing	63	37
	3.0	Housing	35	29
	6.0	Housing	52	36
	3.0	Housing	25	9
Lynch et al. (2007)	6.0	Housing	32	38
Lynch et al. (2008)	5.0	Housing	35	59
Madrid et al. (2013)	1.0	Housing	20	–
	2.0	Housing	27	–
	1.0	Housing	9	–
O’Connell et al. (2006)	6.0	Storage	6	13
	6.0	Storage	24	17
O’Shea et al. (2009)	5.0	Housing	12	37
Panetta et al. (2006)	0.4	Housing	13	–
	2.9	Housing	57	–
	2.5	Housing	51	–

Table 1 continued

Study	CP reduction (%-points)	Emissions measured at	NH_3 reduction (%)	TAN reduction (%)
Portejoie et al. (2004)	4.0	Application	0	27
	8.0	Application	52	55
	4.0	Application	52	38
	4.0	Housing	33	–
	8.0	Housing	76	–
	4.0	Housing	64	39
	4.0	Storage	24	27
	8.0	Storage	64	55
	4.0	Storage	53	38
Average			38	34

Table 2 Impacts of reduced CP in animal diets on NH_3 emissions and TAN content in manure measured at different manure management stages in cattle production systems

Study	CP reduction (%-points)	Emissions measured at	NH_3 reduction (%)	TAN reduction (%)
Agle et al. (2010)	0.5	Storage	15	14
	2.0	Storage	27	29
	2.5	Storage	38	39
Arriaga et al. (2010)	1.8	Housing	32	22
	2.8	Housing	34	22
	1.0	Housing	4	0
Frank and Swensson (2002)	4.6	Housing	66	–
	4.8	Housing	62	–
James et al. (1999)	1.4	Storage	28	19
Koenig et al. (2013)	2.0	Housing	45	–
	1.4	Housing	22	–
Külling et al. (2001)	2.5	Storage	47	46
	2.5	Storage	48	42
	2.5	Storage	41	52
	2.5	Storage	48	49
	5.0	Storage	69	74
	5.0	Storage	73	70
Lee et al. (2012)	1.9	Application	49	24
	1.9	Storage	47	38
Misselbrook et al. (2005)	5.0	Application	70	67
Average			43	38

Statistical analysis

A descriptive statistical analysis of emission reductions was performed to estimate the mean emission reductions along with the standard deviation (SD), sample size, maximum and minimum values. Regression analysis was used to determine the relationships between NH_3 emission reductions, TAN reductions and the CP traits (CP reductions, initial CP and final CP levels) along with their associated interactions.

Three models were tested for cattle and pigs separately to understand whether statistically significant relationships exist between Model 1 (p = pigs, c = cattle): CP traits and NH_3 reductions; Model 2 (p and c): CP traits and TAN reductions; Model 3 (p and c): TAN reductions, final and initial CP on NH_3 reductions. As CP reduction, initial CP and final CP are linearly dependent, only two of these CP traits can be used in the same model. This leads to four different combinations within a model for each combination of CP traits that needs to be compared. However, since initial and final CPs cannot be included without the main effects—CP reductions and TAN reductions, only three combinations were considered. The criterion for the best suited model was the highest adjusted R^2. All regression analyses and selections were done with the REG procedure in the statistical software SAS 9.4 (SAS Institute Inc., Cary, NC, USA).

A fixed-effect analysis of covariance (ANCOVA) model was fitted to combine the data of the two species, pigs and cattle, with the aim to test if there were differences between the species with respect to NH_3 emission reductions. In addition, the models were also tested to check if measurement stage and animal category were significant in explaining NH_3 emission reductions. For comparison between the models the SD of the residuals was considered, with the better fit indicated by a lower SD. All ANCOVA models were analysed with the MIXED procedure of SAS 9.4. All factors were tested at a significance level of 0.05. Differences between class levels of significant factors were tested in post hoc *t* tests. When interactions between class effect and regression effect were significant, differences were tested at a range of values of the dependent variable to identify ranges where the class factors are different. For multiple pairwise comparisons between least squares means, the "simulate" option was used to keep the global significance level of 0.05.

Results

Relationship between CP traits, TAN and NH_3 emissions for pigs

Descriptive statistics of NH_3 emissions with reduced CP in pig diets show average NH_3 reductions of 38 ± 19% (n: 47, Max: 76%, Min: 0%). Averaging the emission reductions over a %-point reduction in CP shows a 11 ± 6% (n: 47, Max: 32%, Min: 0%) decrease in NH_3 emissions. Testing the relationship of NH_3 reductions with CP traits indicates an influence of CP reduction, final CP and an interaction between CP reduction and final CP at an adjusted R^2 of 0.53 (RMSE = 13.54). In the final model, only CP reduction and the interaction between CP reduction and final CP were statistically significant ($p < 0.05$). However, since the interaction terms cannot be included without the main effect, final CP was part of the model as well.

$$E_a = -11.48 + 27.61\,CP_{red} + 2.46\,F_{cp} - 1.74\,(CP_{red} \times F_{cp}) \qquad \text{(Model 1 [p])}$$

where E_a is the NH_3 reduction (%); CP_{red} is the CP reduction (%-point); F_{cp} is the final CP level (%).

Figure 1 illustrates Model 1 [p] and shows that high reductions of NH_3 can be achieved when the final CP level is low and the reductions in CP are high. Descriptive coefficients of the emissions estimates indicate that reduced CP in pig diets led to reductions of TAN by 34 ± 16% (n: 34, Max: 64%, Min: 3%). Average reductions in TAN per %-point reduction in CP was 8 ± 3% (n: 34, Max: 13%, Min: 1%). Investigating the effect of CP traits on TAN reductions through a regression analysis indicates an influence of CP reduction and final CP at an adjusted R^2 of 0.56 (RMSE = 12.81). All the factors included in the model were statistically significant ($p < 0.05$).

$$TAN_{red} = 52.27 + 4.55\,CP_{red} - 2.82\,F_{cp} \qquad \text{(Model 2 [p])}$$

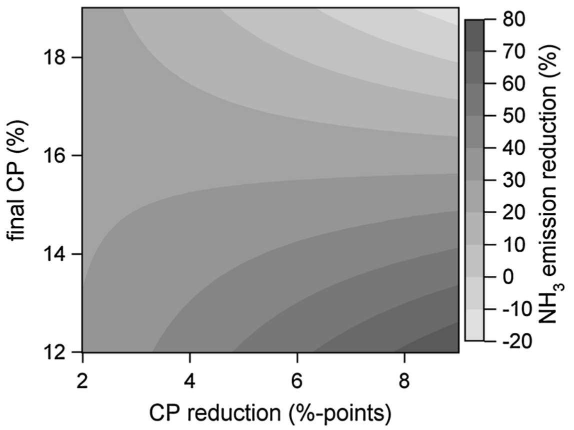

Fig. 1 Relationship between CP traits and its effect on NH_3 emission reductions in pig production systems

where TAN_{red} is the TAN reduction (%).

Testing for whether TAN is the primary driver of NH_3 emissions reveals a similar relationship to that of CP traits and NH_3 reductions as in Model 1 [p]. The final model chosen includes TAN reductions, final CP and the interaction of TAN reductions with final CP at an adjusted R^2 of 0.58 (RMSE = 12.81). Only TAN reductions and the interaction between TAN reductions and final CP were statistically significant ($p < 0.05$). However, since the interaction term is significant, the main effect had to be added to the final model.

$$E_a = -29.23 + 4.16\,TAN_{red} + 3.22\,F_{cp} - 0.26\,(TAN_{red} \times F_{cp}) \qquad \text{(Model 3 [p])}$$

NH_3 emission reductions also varied based on the manure management stage at which they were measured. Estimates from a descriptive analysis of the observations show reductions of 11 ± 6% (n: 26, Max: 32%, Min: 1%) for housing, 6 ± 5% (n: 5, Max: 13%, Min: 1%) for storage and 7 ± 7% (n: 3, Max: 13%, Min: 0%) for application when averaged over a %-point reduction in CP. Differences in NH_3 emission reductions also existed between pig categories. Gilts and barrows had NH_3 reductions of 12 ± 7% (n: 22, Max: 32%, Min: 0%), whereas boars showed reductions of 7 ± 5% (n: 11, Max: 18%, Min: 1%) when averaged over a %-point reduction in CP. The ANCOVA method was used to test the influence of manure stages and animal category on the extent of NH_3 reductions from reduced CP using the best fitted Model 1 [p]. The analysis showed that although there were variations in emission estimates, no statistically significant difference exists to indicate that measurement stage and animal category influence NH_3 emission reductions.

Relationship between CP traits, TAN and NH_3 emissions for cattle

Descriptive statistics of NH_3 emission reduction estimates for cattle with reduced CP report average emission reductions of 43 ± 18% (n: 20, Max: 73%, Min: 4%). The average emission reductions per %-point CP reductions show a decrease in NH_3 emissions by 17 ± 6% (n: 20, Max: 30%, Min: 4%). Testing for the relationship between CP traits and NH_3 emissions reveals a close relationship between NH_3 emissions and CP reduction with an adjusted R^2 of 0.80 (RMSE = 8.46, $p < 0.05$).

$$E_a = 11.04 + 12.02\,CP_{red} \qquad \text{(Model 1 [c])}$$

Figure 2 illustrates this relationship and shows that greater reductions of NH_3 can be achieved at high CP reductions. Contrary to the case in pigs, there was no influence of final CP on NH_3 emission reductions. TAN content of manure also decreases with a reduction of CP in cattle diets. A descriptive statistical analysis of TAN estimates show reductions of 38 ± 21% (n: 16, Max: 74%, Min: 0%) and 15 ± 6% (n: 16, Max: 27%, Min: 0%) when averaged over a %-point reduction in CP. Testing the relationship of TAN reductions with CP traits revealed a strong relationship with TAN and CP reduction at an adjusted R^2 of 0.80 (RMSE = 8.46, $p < 0.05$).

$$TAN_{red} = 2.27 + 13.98\,CP_{red} \qquad \text{(Model 2 [c])}$$

Investigating whether NH_3 reductions were driven by TAN along with initial and final CPs showed a strong functional relationship between NH_3 reductions and TAN at an adjusted R^2 of 0.85 (RMSE = 7.41). TAN reductions were statistically significant in the model ($p < 0.05$).

$$E_a = 10.25 + 0.83\,TAN_{red} \qquad \text{(Model 3 [c])}$$

A descriptive statistical analysis of the role of different manure stages on NH_3 emission reductions from reduced CP in cattle indicates differences in estimates. Estimates showed reductions of 14 ± 6%

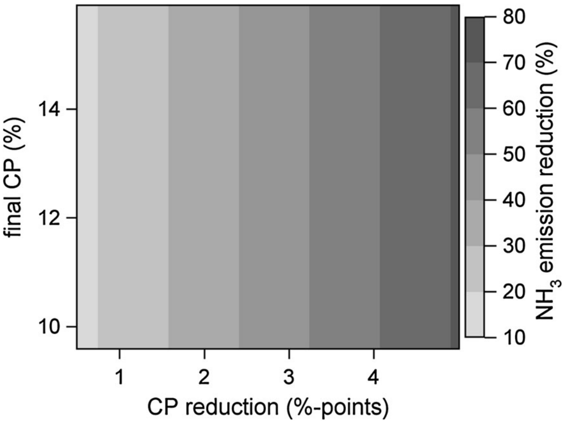

Fig. 2 Relationship between CP traits and its effect on NH_3 emission reductions in cattle production systems

(n: 7, Max: 22%, Min: 4%) for housing, 19 ± 5% (n: 11, Max: 13%, Min: 1%) for storage and 7 ± 7% (n: 2, Max: 13%, Min: 0%) for application when averaged over a %-point reduction in CP. However, similar to the case in pigs, these differences between measurement stages were not statistically significant when tested using an ANCOVA method.

Differences in NH_3 emissions between pigs and cattle following reduced CP in diets

The differences between cattle and pigs with respect to NH_3 emission reductions were compared using an ANCOVA method. The best fitted models that explained NH_3 emission reductions for both pig and cattle, Model 1 [p] and Model 1 [c] were tested against each other. This involved the addition of a class effect for species as a main effect, as well as the interactions between regression factors.

Testing the difference between cattle and pigs using Model 1 [p] indicates an influence of CP reduction, final CP and the interaction between initial and final CP for both cattle and pigs. All the factors included in the model along with the interaction between CP reduction and species type were statistically significant ($p < 0.05$). The empirical equations, Model 1 [pm = pig model, p = pig] and Model 1 [pm, c = cattle] along with the parameter estimates are reported below.

$$\text{Pigs: } E_a = 0.43 + 24.53\,CP_{red} + 1.57\,F_{cp} - 1.51\,(CP_{red} \times F_{cp}) \qquad (\text{Model 1 [pm, p]})$$

$$\text{Cattle: } E_a = -22.23 + 32.2\,CP_{red} + 2.51\,F_{cp} - 1.51\,(CP_{red} \times F_{cp}) \qquad (\text{Model 1 [pm, c]})$$

Figure 3 illustrates the difference between cattle and pigs when tested against each other at varying levels of CP reductions and final CP. Similar to the case in pigs (Model 1 [p]), the figure shows that greater NH_3 emission reductions are obtained with high CP reduction and low final CP for both animal types. The difference between cattle and pigs are significant for all levels of final CP when CP reductions are greater than 3.5%. However, as the final CP level increases, the difference between cattle and pigs are significant

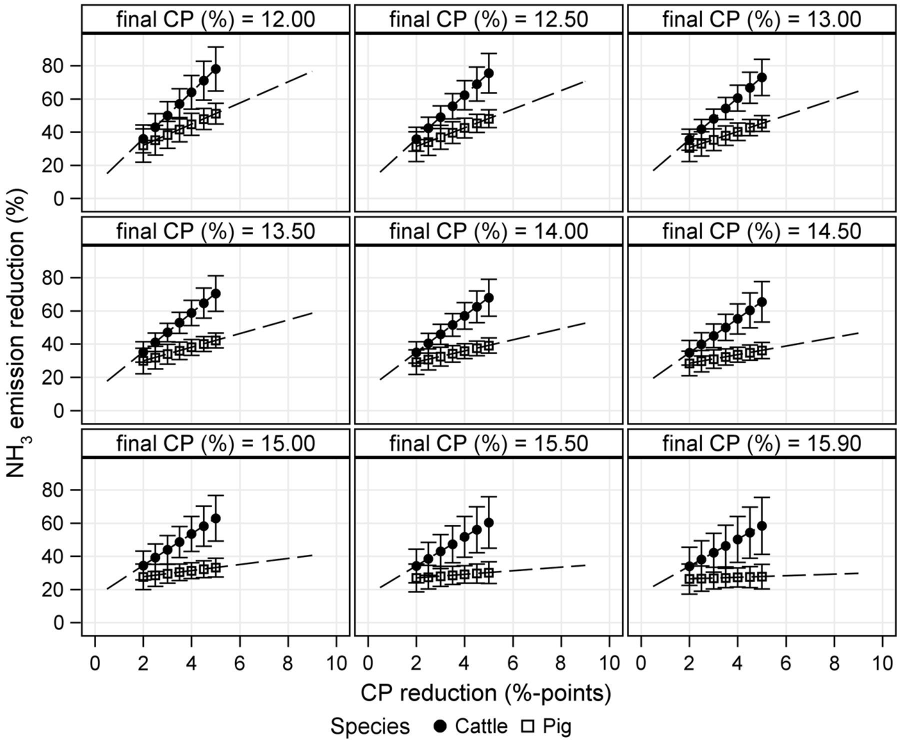

Fig. 3 NH_3 emission reductions for cattle and pigs under varying CP reductions and final CP levels using the pig model

even at lower CP reductions. The slopes of the graphs between pigs and cattle shows that even at low CP levels, the NH_3 reductions for a particular CP reduction is higher for cattle than pigs. For example, at a final CP level of 12%, a CP reduction of about 5%-points in cattle diets could reduce NH_3 emissions by 80%. However, in the case of pigs, to achieve the same NH_3 reductions at a final CP level of 12%, the CP reductions would have to be in the order of 9%-points. This is also reflected in the parameter estimates of the slopes for both cattle and pigs. Slopes for CP reduction shows that a reduction in CP is 31% more effective in reducing NH_3 emissions for cattle as compared to pigs. Even when it comes to slopes of final CP, cattle were 60% more effective in reducing NH_3 emissions relative to pigs.

Examining the difference between cattle and pigs using Model 1 [c] reveals an influence of CP reduction on both animal types ($p < 0.05$). The interaction between species type and CP reduction was also significant ($p < 0.05$). The empirical equations, Model 1 [cm = cattle model, p = pig] and Model 1 [cm, c = cattle] along with the parameter estimates are reported below.

$$\text{Pigs: } E_a = 13.08 + 5.61\,CP_{red} \qquad (\text{Model 1 [cm, p]})$$

$$\text{Cattle: } E_a = 11.04 + 12.02\,CP_{red} \qquad (\text{Model 1 [cm, c]})$$

Figure 4 illustrates the difference between cattle and pigs when tested against each other at varying levels of CP reductions. Similar to the case in cattle (Model 1 [c]), the figure shows that greater NH_3 emission reductions are achieved with high CP reduction for both animal types. The difference between cattle and pigs are significant when CP reductions are greater than 2.5%. The slopes in Fig. 4 show that cattle are more sensitive to CP reductions and have higher NH_3 reductions than pigs for a similar CP reduction. The parameter estimates for the slopes indicate that cattle were 53% more effective in reducing NH_3 emissions as compared to pigs.

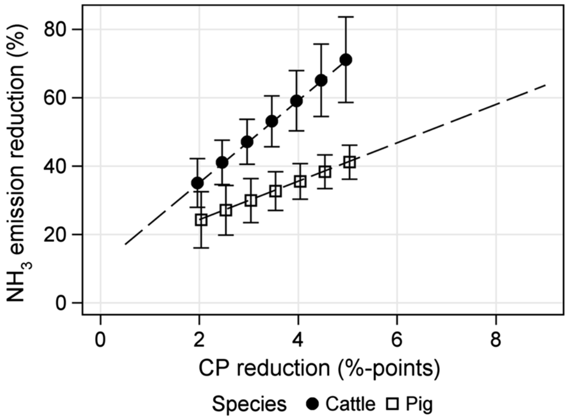

Fig. 4 NH_3 emission reductions for cattle and pigs under varying CP reductions and final CP levels using the cattle model

Discussion

Implication of reduced CP on NH_3 emissions in cattle and pigs

The results presented confirm the expectation that there is potential to reduce NH_3 emissions by lowering CP in animal diets. Overall averages of emission estimates considered in this study report NH_3 reductions of 17 ± 6% per %-point CP for cattle relative to 11 ± 6% for pigs. The higher reductions in NH_3 emissions for cattle relative to pigs were also statistically significant when tested against each other. Since the NH_3 emission reductions calculated in this study were based on measured emission reductions from published literature, a direct comparison of emission estimates and relationships with those from experimental studies was not possible. Additionally, studies that have reviewed the emission reductions from reduced CP in animal diets distinguishing between cattle and pigs are rare. The United Nations Economic Commission for Europe's (UNECE) document on NH_3 abatement reports NH_3 reductions in the range of 5–15% for each %-point reduction in CP content in animal diets (Oenema et al. 2014). The relationships between CP traits, TAN and NH_3 emissions were better correlated in cattle as compared to pigs. In the case of pigs, NH_3 reductions were dependent on CP reductions and the level of final CP ($R^2 = 0.53$, see Fig. 1). Cattle on the other hand showed a strong correlation between CP reductions and NH_3 emissions ($R^2 = 0.80$, see Fig. 2). The results from an experimental study by Swensson (2003) also indicated a strong relationship between CP reductions and NH_3 emissions for cattle ($R^2 = 0.91$).

An evaluation of factors such as the manure management stage at which NH_3 is measured and pig categories (gilts, barrows and boars) showed differences in mean NH_3 emission reduction estimates. However, a statistical analysis of the effect of the manure management stage at which NH_3 emissions were measured did not reveal a significant influence on NH_3 emission reductions for either cattle or pigs. As far as pig categories are concerned, five studies among the 14 used for the meta-analysis measured the impacts of reduced CP in boars. Boars have a higher protein accretion potential than gilts or barrows (Campbell and King 1982; Campbell and Dunkin 1983; Campbell et al. 1985). Even at a higher CP diet, boars retain a bulk of the protein instead of excreting it. Hence, the effect of a CP reduction in boar diets might not be as pronounced in reducing NH_3 emissions as compared to gilts or barrows. Even though a comparison of the mean emission reduction estimates between boars and gilts/barrows revealed such a relationship, a statistical analysis of the differences was insignificant. A similar analysis could not be performed for cattle since the studies analysed were limited mostly to dairy cattle.

One of the main findings of this study is the higher NH_3 emission reductions with reduced CP along with a clearer trend in relationships between CP, NH_3 and TAN for cattle as compared to pigs. This could be attributed to the specific physiology of ruminants such as cattle, to efficiently recycle nitrogen in situations of low protein intake (Van Soest 1994), leading to a greater cut-down on CP. Additionally, due to the greater attention given to feed optimization in pigs relative to cattle, pig diets used in this study might have already been well balanced as opposed to cattle diets. This imbalance in cattle diets could have then amplified the effect of reducing CP on NH_3 emissions. However the implications of nutrient balance on NH_3 emissions could not be studied in detail here, since the nutrient requirement of animals depend on many factors including genetic background of animals, traits of main (economic) interest and price of nutrients, among others. Tables S.1 and S.2 reports the sources, feed composition and initial and final CP levels of studies included in the meta-analysis which could be used to investigate the relationship between protein balance and its influence on NH_3 emissions.

Despite the higher reductions of NH_3 as pointed out in this study, cattle have received relatively less attention than pigs in terms of implementing specific feeding strategies as a means for reducing NH_3. This is probably due to the following reasons: Pig production systems are standardized based on conceptual logics of industrial production, whereas cattle production systems are much more heterogeneous (Raney et al. 2009), which is paralleled by restricted possibilities for practical process control. Due to the standardisation of pig production systems over the last five decades, pig production was gradually disconnected from the land area utilized for feed production which allowed for a concentration of large herds on relatively small areas of land (Marquer 2010; Thornton 2010), where the environmental impact became more obvious. In addition, due to the function of the symbiotic rumen microbiota, ruminants like cattle are less dependent on highly digestible, protein-rich feeds which are typical in pig production systems. Hence dietary manipulation concepts such as reduced CP and external amino acid supplementation have been implemented in pig production relatively early, in order to, among other advantages, abate NH_3 emissions. With the growing demand for milk and meat dictating a higher production efficiency and performance in cattle, the capacity of rumen symbionts might not be enough to meet the animal requirements. In this case, cattle diets may also be supplemented with certain external protein and amino acid supplements, which are likely to influence NH_3 emissions (Robinson 2010). There is also the risk of an oversupply of protein in traditional production systems, where cattle feed on physiologically young grass, which is rich in protein, particularly in spring and autumn (Van Soest 1994). Hence, in various production systems, CP in cattle diets might be (temporarily) in excess of the animal requirements. The larger NH_3 abatement and the more direct relationship of CP with NH_3 and TAN in the case of cattle highlight an opportunity to further reduce NH_3 emissions from livestock manure.

Additional factors influencing NH_3 emission reductions

The wealth of information collected from literature in this study allowed to further discern effects on NH_3 emissions beyond those tangible by statistical analysis. A statistical evaluation of these factors was not possible due to limited data availability However, a discussion of these factors is important in the prospective design of emission measurement studies and also to fully assess NH_3 emission abatement from reduced CP in animal diets.

Manure management systems

Variability in emission reductions could arise from the differences between manure management systems. Studies have shown that the type of housing, storage and application methods associated with different manure management systems influence emissions of NH_3 (Amon et al. 2001; Külling et al. 2001; Webb et al. 2010). For example, a study by Külling et al. (2001) measured the effect of reduced CP on NH_3 emissions for various storage types ranging from slurry, urine rich slurry, farmyard manure and deep litter. The NH_3 emission reductions showed substantial variation in the range of 9–30% per %-point reduction in CP, highlighting the variability associated with different storage types on NH_3 emission patterns. A detailed investigation separating the effect of manure management systems on NH_3 emissions is beyond the scope of this analysis. However, proper categorization and consideration of differences between manure management systems during measurement and quantification of emission reductions could help reduce variability in emission estimates.

Nutritional factors

The studies used in this analysis were all checked for fulfilment of the animals' nutritional requirements. One of the studies excluded from the analysis involved unrealistic CP levels in pig diets. The levels of CP fed were around 6%, which may be useful for metabolic or physiological studies, but lack practical relevance. Also, the level of external amino acid supplements was on the lower side, which resulted in a supply of essential amino acids around 25% below the requirement during the growing stage (Otto et al. 2003).

The type of CP fed also influences the N flow in manure and subsequent NH_3 emissions. In terms of pigs, most studies used soybean products as a source of CP. However, in the case of cattle, both soybean and urea were used as a source of protein and non-protein nitrogen, respectively. Urea is immediately degradable in the rumen, while true proteins like soybean take some time to degrade (Van Soest 1994). Analysing the rumen degradability of protein sources might be a way to address comparability issues between studies with ruminants that involve similar CP reductions, but include different protein sources.

Physiological stage

The physiological stage of animals could also influence the excretion rate and NH_3 emissions. In the early growing stage the N retention is low as compared to the finishing phase. In physiological stages where the N retention rate and hence the protein and amino acid requirement of the animal is low, a reduction of CP that is beyond requirement will have a large impact on reduction of NH_3 emissions. Hernández et al. (2013) showed that the NH_3 emission reductions from growing pigs were higher than the finishing phase, when subject to the same level of CP reduction. Montalvo et al. (2013) measured reductions in NH_3 from decreasing CP in piglets. The authors found NH_3 reductions near 20% per %-point of CP. Although this looks promising, the practical implication needs to be questioned, since piglets consume relatively small amounts of feed over a limited period of time and hence the potential of cutting down CP in their diets to reduce NH_3 emissions is rather low. In the case of cattle, a similar comparison could not be made since NH_3 emission reduction experiments for growing cattle subject to reduced CP were not available in the dataset. Accounting for metrics such as N retention levels could help in further analysing results from studies that involve different physiological stages of animals.

Conclusions

This meta-analysis confirms that CP in animal diets and emissions of NH_3 show a clear relationship. The meta-analysis revealed mean NH_3 reduction of 17 ± 6% per %-point CP for cattle and 11 ± 6% for pigs. Analysis of variability in NH_3 emission reductions due to emissions measured at different manure management stages and across pig categories showed trends, but not a significant influence. Statistical models showed that significant relationships exist between reduced CP, TAN content in the manure and NH_3 emissions for both animal types. Testing the difference between cattle and pigs indicates significant differences between both animal types with higher NH_3 reductions for cattle as compared to pigs, following a reduction of CP in animal diets. This increased reduction along with a clearer trend in relationships between CP and NH_3 emissions for cattle is very relevant in terms of agricultural policy, since in the past, efforts to reduce NH_3 emissions via dietary manipulation were targeted primarily towards pigs. With increasing pressure on agriculture to tackle its nitrogen footprint, extending the concepts of feed optimization from pig and poultry diets to cattle can provide an additional pathway to further reduce NH_3 emissions from livestock manure. This study improves the current knowledge by quantitatively analysing NH_3 reduction potentials per %-point CP reduction and evaluating the relationships between CP traits, TAN content in the manure and NH_3 reductions.

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