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Pilot study: Evaluation of the ammonia emission potential of free stall dairy barns when combining mitigation measures

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The national emission reduction commitments (NEC) require the use of NH_3 mitigation measures on livestock farms. In this pilot study, an innovative barn construction project from an EIP Agri project in Baden-Württemberg was used as an example to analyse how a combination of measures affects the NH_3 emission potential of free stall dairy barns. For this purpose, a method for the evaluation of the NH_3 emission potential based on a multiplication of mitigation factors was developed and applied. For the example barn with an exercise yard, a lower emission potential per animal place and year could be determined than for a standard cubicle barn without an exercise yard. However, a reduction of the total emission potential of the example farm compared to the initial situation was not possible due to the doubling of the herd size in the course of the new construction. Nevertheless, the study showed potential for the compatibility of animal welfare and NH_3 emission reduction in dairy cow husbandry.

Keywords
Ammonia, dairy cattle, emission reduction, combination of measures, barn construction

The EU directive on the reduction of national emissions of certain atmospheric pollutants (National Emission Ceilings (NEC)) obligates Germany to a reduction of ammonia emissions by 5 % until 2020 and by 29 % until 2030 compared to the reference year 2005 (Richtlinie (EU) 2016/2284). 95 % of German ammonia emissions are caused by agriculture (UBA 2018). In order to reduce these, structural and technical measures within the barns must be taken in addition to the measures for storing and spreading the manure (Eurich-Menden et al. 2018). In cattle barns, ammonia (NH_3) is formed through contact between urine and faeces by the enzymatic cleavage of the urea from the urine using the enzyme urease from faeces or from areas soiled with faeces (Monteny and Erisman 1998, Braam and Swierstra 1999). Since emissions increase with the size of the emitting surface (Monteny and Erisman 1998, Braam and Swierstra 1999, Snoek et al. 2014), the emission factor triples to 14.57 kg NH_3 per animal place (pl) and year due to the conversion from tie stall to free stall barns (VDI 3894-1 2011). The high priority given to animal welfare within the framework of the agricultural investment promotion programme (AFP) in Baden-Württemberg could also lead to an increase in emissions. The reason for this is the larger area per animal, which is mainly a result of the construction of an exercise yard under the *AFP premium* funding. This shows the much-discussed conflict of objectives between emission reduction and animal welfare (WBA 2015).

The EIP Agri project "Construction in Cattle Farming" (EIP Cattle) aims to resolve this conflict of objectives through innovative concepts and measures in barn construction. By the end of 2022, more than 20 barn construction projects will be planned and realised together with farmers and serve as

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lighthouse projects in Baden-Württemberg with scientific support. The innovation of these barn constructions consists, among other things, of the combination of several structural and technical NH_3 mitigation measures, which at the same time allow synergy effects to be expected for animal welfare. In order to be able to estimate the potential of the combinations of measures, this pilot study developed and applied a corresponding method to evaluate the NH_3 emission potentials of free stall dairy barns. Additionally, the investment costs of the measures used were calculated.

Structural and technical measures for NH_3 emission reduction in free stall dairy barns and their potential synergy effects for animal welfare

Elevated feed stalls can contribute to the reduction of NH_3 emissions from the dairy cattle barn by reducing the soiled area (Zähner et al. 2019) and allowing a higher manure scraping frequency in the feed alley without disturbing the cows during feed intake (Benz et al. 2014, Zähner et al. 2019). Feeding place partitions at every second feeding place prevent cows from turning around and defecating on the floor when leaving the feed stall (EIP-Rind 2019, Zähner et al. 2019). They also reduce the displacement from the feeding place by higher ranking animals (Benz et al. 2014, Zähner et al. 2019).

However, the highest potential for emission reduction in naturally ventilated free stall barns probably lies in the design and cleaning of the walking areas (Eurich-Menden et al. 2018). The principle for the reduction of emissions from solid floors is based on the rapid drainage of urine (Schrade et al. 2017). This can be achieved by frequent manure removal of V-shaped solid floors with 3 % slope towards a central urine gutter (Braam et al. 1997, Steiner et al. 2012, Schrade et al. 2017) or grooved solid floors (Swierstra et al. 2001, Zähner 2005, VDI 3894-1 2011). The NH_3 mitigation potential of different slatted floor designs is also explained by a rapid drainage of urine as well as a reduction of the gas exchange between the manure channel and the barn (Eurich-Menden et al. 2018).

In addition to structural mitigation measures, the alley surfaces can be moistened (Braam et al. 1997, Zähner and Schrade 2020) and the frequency of manure removal can be increased (Eurich-Menden et al. 2018). By moistening the alleys before removing the manure with the scraper, smear layers are avoided, and a better cleaning result is achieved (Zähner et al. 2017). The alleys can be moistened by means of devices in the cubicle and feed stall kerb or the manger wall (Testate EIP-Rind o.J.) as well as by a cow shower in case of suitable relative humidity of the air (Zähner and Schrade 2020, Testate EIP-Rind o.J.). The latter simultaneously reduces the heat stress of the cows (Gasteiner 2014). Frequent manure removal ensures that the surfaces are clean (Zähner et al. 2005) and that urine can drain off unhindered (Schrade and Steiner 2012). Eurich-Menden et al. (2018) state that the alleys should be scraped at least every two hours to reduce emissions. At 12 manure removal events a day, positive effects on the cleanliness of the claws (Zähner et al. 2019) and thus on their health (Heinz et al. 2011, Schrade et al. 2013) are also apparent.

The exercise yard causes additional emissions of 8 g NH_3 m^{-2} d^{-1} (VDI 3894-1 2011). Structuring the exercise yard with unroofed cubicles and additional feed stalls is intended to reduce the emitting surface and thus contribute to the reduction of emissions (Testate EIP-Rind o.J.). Additional, emission-reducing floors and stationary manure scrapers can be installed on structured exercise yards. Structuring also makes it possible to integrate the exercise yard into the daily routine of the cows, as recommended by Van Caenegam and Krötzl Messerli (1997), by enabling the behaviours described in Kerbrat and Disenhausen (2004) (walking, standing, lying down, standing in the cubicle, eating and drinking) to be performed outside. Otherwise the cows usually have little time to use the exercise yard (Van Caenegam and Krötzl Messerli 1997). The reduced walking area per animal on structured exercise yards is not accompanied by a loss of animal welfare, since the size of the area is less important for its evaluation than its attractiveness for the cow (Van Caenegam and Krötzl Messerli 1997, Schrade et al. 2010).

The aim of the pilot study was first to develop a method to evaluate the NH_3 emission potential per dairy cow and year when the above described mitigation measures are combined in cubicle barns, and in a second step to evaluate the emission potential of an EIP Cattle barn as an example.

Material and methods

As an example of a barn, a cubicle barn with a structured exercise yard was selected, which was built in accordance with the guidelines of the *AFP premium* funding in Baden-Württemberg. Within the framework of the EIP project, up to 25 % of the required exercise yard area of at least 4.5 m^2 LU^{-1} for one third of the dairy cows (VWV Einzelbetriebliche Förderung 2014) may be structured for research purposes (Ministerium für Ländlichen Raum und Verbraucherschutz, Stuttgart: personal communication on 13 Dec 2017). For the barn example, the unroofed walking area is reduced from 248 m^2 to 201 m^2 by structuring 19 % of the exercise yard. The farm is managed conventionally and increased its livestock from 81 (average herd size 2015-2017) to 165 cows in the course of the barn construction. The barn floor plan (Figure 1) provides an overview of the most relevant NH_3 mitigation measures of the example barn.

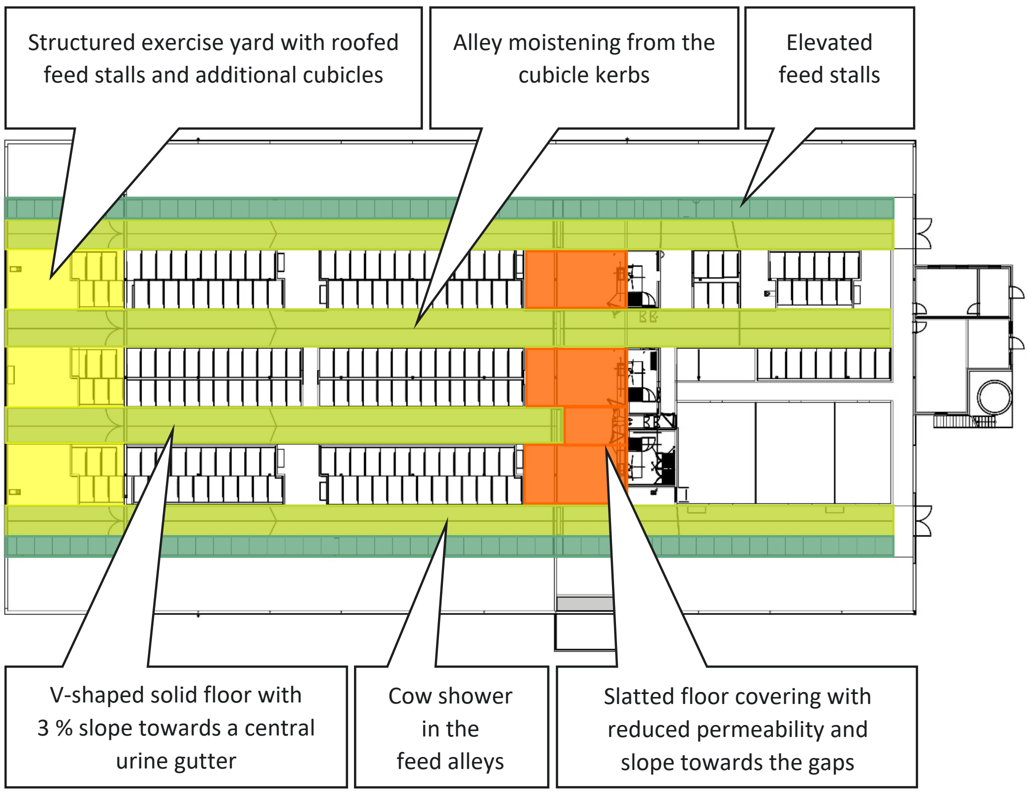

Figure 1: Floor plan of the barn example from the EIP Cattle project including explanations of the most relevant emission mitigation measures

The emission mitigation measures are assigned to different categories (Table 1) required for the evaluation: "reduction of emitting surfaces", "emission-reducing floor designs" and "accompanying measures". The latter, however, are not directly included in the evaluation, but are considered to be accompanying necessities in order to achieve the calculated emission potential in practice. In addition, Table 1 shows the net investment costs that are used to calculate the additional costs for the structural and technical NH_3 mitigation measures. These were requested from several companies and are to be considered as guiding prices, which may vary depending on the barn, location and supplier company. The slatted floor design used around the milking robots in the barn example is characterized by a 28 % reduction in permeability and a convex surface with slope towards the gaps. As there are currently no studies available on practical farms, the mitigation potential of this floor design was conservatively estimated at 20 %.

Table 1: Structural and technical NH_3 mitigation measures used in the example barn, their NH_3 mitigation potential and factor as well as the corresponding net investment costs (FP: feeding place; rm: running metre)

Measure	Mitigation potential	Mitigation factor	Investment costs (plus VAT, incl. installation)		
Reduction of emitting surfaces					
Elevated feed stall (free stall barn)	15.5 % (calculated on the basis of Zähner et al. 2019)	0.845	186	€ FP^{-1}	(Seiler 2019a)[1]
Elevated feed stall (exercise yard)	Results from the reduced walking area		186	€ FP^{-1}	(Seiler 2019a)
Unroofed cubicles (exercise yard)	Results from the reduced walking area				
Moveable concrete pedestal			613	€ $pc.^{-1}$	(Gröber 2019)[2]
Cubicle partition			329	€ $pc.^{-1}$	(Gröber 2019)
Rubber mat			123	€ m^{-2}	(Gröber 2019)
Emission-reducing floor designs					
V-shaped solid floor with 3 % slope towards a central urine gutter	20 % (VDI 3894-1 2011)	0.8			
Urine gutter			66	€ rm^{-1}	(Hornstein 2018)[3]
Rubber mat			72	€ m^{-2}	(Gröber 2019)
Slatted floor covering with reduced permeability and slope towards the gaps	20 % (estimate)	0.8	85	€ m^{-2}	(Gröber 2019)
Accompanying measures					
Alley moistening	–	–	25	€ rm^{-1}	(Hornstein 2018)
Cow shower	–	–	60	€ rm^{-1}	(Seiler 2019b)[4]

1) personal communication on 18 Feb 2019
2) personal communication on 13 Feb 2019
3) personal communication on 28 Dec 2018
4) personal communication on 28 Jan 2019

In previous methods developed for modelling the NH_3 emission potentials of free stall dairy barns at farm level (Rotz et al. 2014, Kupper 2018), the calculation is based on the excreted amount of total ammonia nitrogen (TAN). In contrast, the method presented here is based on the emission factors of VDI 3894-1 (2011). These are based on an expert estimate (Eurich-Menden et al. 2010) and amount to 14.57 kg NH_3 pl^{-1} a^{-1} for cubicle barns and 8 g NH_3 m^{-2} d^{-1} for exercise yards (VDI 3894-1 2011).

When combining several mitigation measures, it should be noted that the mitigation potentials cannot be added up in full (VDI 3894-1 2011).

Against this background, the following assumption could be derived from logical correlations: First, NH_3 emissions from free stall dairy barns are reduced by less urea excretion in the barn. The remaining NH_3 emission potential is reduced by a reduction of the emitting surfaces. The subsequently remaining emission potential is in turn reduced by the emission-reducing properties of the measures applied on the areas. Based on this assumption, the measures were divided into categories (Table 1) and led to the following basic formula (Equation 1), which is based on the multiplication of the emission factor with the mitigation factors of all measures used.

$$\boldsymbol{NH_3EP_b\left[\frac{kg\ NH_3}{pl\ \times\ a}\right] = NH_3EF_b\left[\frac{kg\ NH_3}{pl\ \times\ a}\right] \times MF_{ru} \times MF_{rs} \times MF_{fd}} \qquad \text{(Eq. 1)}$$

NH_3EP_b: NH_3 emission potential free stall barn
NH_3EF_b: NH_3 emission factor free stall barn
MF_{ru}: Mitigation factor “reduction of urea excretion in the barn”
MF_{rs}: Mitigation factor “reduction of emitting surfaces”“
MF_{fd}: Mitigation factor “emission-reducing floor designs”
pl: animal place

In addition to the structural and technical mitigation measures on which this study focuses, other organisational measures to reduce NH_3 emissions can be applied besides moistening the alleys and adjusting the manure removal frequency. These include N-adapted feeding and grazing (VDI 3894-1 2011). Both measures are to be assigned to the category “reduction of urea excretion in the barn”, which was included in the basic formula (Equation 1) for the sake of completeness.

To evaluate the emission potential of the structured exercise yard (Equation 2), the emission factor for the exercise yard according to VDI 3894-1 (2011) is used. Only the unroofed walking areas are included into the calculations. The area of the exercise yard is therefore reduced by the area for the cubicles and feed stalls. As there have been no studies on the use of emission-reducing floor designs on the exercise yard so far, it was assumed that 50 % of the mitigation potential related to the free stall barn (Table 1) can be transferred to the area of the exercise yard. A lower mitigation potential on the exercise yard is assumed due to the emission-promoting effect of direct sunlight (Zähner et al. 2005) and increased wind speeds (Brose et al. 1999, Schrade et al. 2011).

$$\boldsymbol{NH_3EP_{sey}\left[\frac{kg\ NH_3}{pl \times a}\right] = \frac{NH_3EF_{ey}\left[\frac{g\ NH_3}{m^2 \times d}\right] \times A_{uw}[m^2] \times 365 \times (1 - 0{,}5MP_{fd})}{pl\ [n] \times 1000}} \qquad \text{(Eq. 2)}$$

NH_3EP_{sey}: NH_3 emission potential structured exercise yard
NH_3EF_{ey}: NH_3 emission factor exercise yard
A_{uw}: Unroofed walking area
MP_{fd}: Mitigation potential “emission-reducing floor designs”
pl: animal place

The NH_3 emission potentials for the free stall barn and the exercise yard are added up and designated as annual NH_3 emission potential per dairy cow and total annual NH_3 emission potential of the free stall dairy barn. They represent the ideal case and apply under the condition that the necessary accompanying measures are met as follows: The manure scraper runs at least 12 times a day and the alleys are moistened before manure removal to improve the cleaning result. An overview of the developed method is shown in Figure 2.

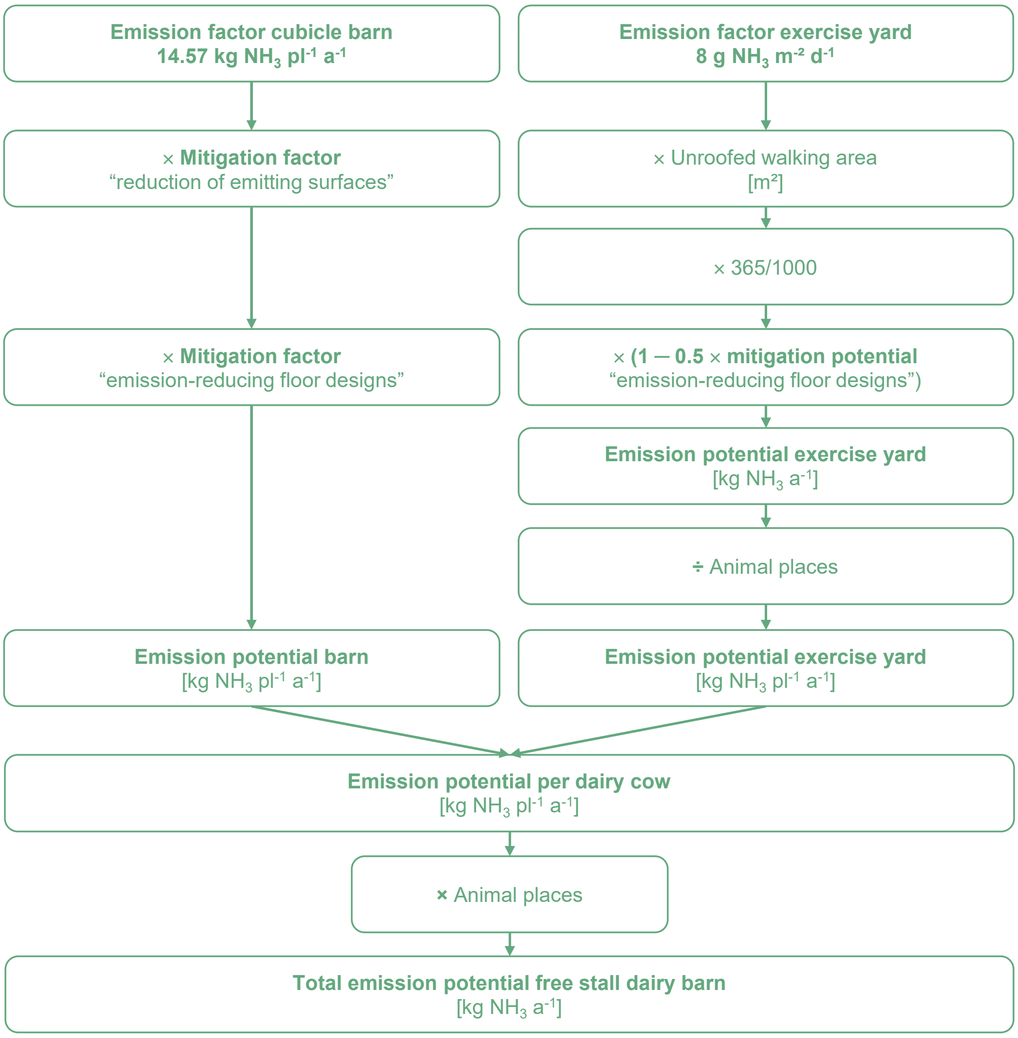

Figure 2: Schema of the evaluation of the NH_3 emission potentials of cubicles barns with exercise yard under consideration of structural and technical mitigation measures

The pilot study compared the emission potentials of the housing systems described in Table 2. The emission factor for cubicle barns (VDI 3894-1 2011) corresponds to the annual NH_3 emission potential per dairy cow for the *Standard* system. The old barn, which was previously managed on the example farm, also belongs to the *Standard* system without emission mitigation measures. The old barn can be retrofitted to the *StandardPLUS* barn by installing elevated feed stalls and emission-reducing floors including alley moistening. The choice was made to adopt the combination of the above-mentioned mitigation measures, as these are the same measures that are also used in the *AFP PremiumPLUS* barn. For comparison purposes, the total NH_3 emission potential of the *Standard* system and the retrofittable *StandardPLUS* system was evaluated for the average herd size of the last three years on the example farm (81 cows). For the *AFP Premium* and *AFP PremiumPLUS* barns, the evaluation of the total emission potential was based on the animal places in the new EIP barn (165 pl).

Table 2: Housing systems compared in the pilot study

System	Name	Comment
Standard without emission mitigation measures	*Standard*	Cubicle barn
Standard with emission mitigation measures	*StandardPLUS*	Cubicle barn with elevated feed stalls and an emission-reducing floor design as well as devices for the moistening of the alleys
AFP Premium without emission mitigation measures	*AFP Premium*	Cubicle barn with exercise yard according to the *AFP Premium* requirements in Baden-Württemberg Exercise yard area: 4.5 m^2 LU^{-1} for one third of the cows (VWV Einzelbetriebliche Förderung 2014)
AFP Premium with emission mitigation measures	*AFP PremiumPLUS*	Barn example from the EIP project

Furthermore, the additional costs for the investment and installation of the mitigation measures for the *AFP PremiumPLUS* barn on the example farm were calculated in comparison to the investment costs for an *AFP Premium* barn. Also included are the accompanying measures for the alley moistening via the cubicle kerbs and the cow shower. All prices (Table 1) are net prices including installation. For calculation purposes, Hornstein (personal communication on 28 Dec 2018) will add 25 % of the material costs for installation. This procedure was adopted if no information on the installation costs was provided by the companies involved.

Results

Annual NH_3 emission potential per dairy cow

The *AFP PremiumPLUS* dairy cow barn achieves an NH_3 emission potential of 13.05 kg NH_3 pl^{-1} a^{-1}. Of this, 9.85 kg NH_3 pl^{-1} a^{-1} is accounted for by the barn and 3.20 kg NH_3 pl^{-1} a^{-1} by the exercise yard. Despite the additional emissions from the exercise yard, the emission potential can be reduced by 1.52 kg NH_3 pl^{-1} a^{-1} compared to the *Standard* system. Compared to the *AFP Premium* system, the ammonia emission potential can be reduced by 5.90 kg NH_3 pl^{-1} a^{-1}. The mitigation potential of the structured *AFP PremiumPLUS* exercise yard compared to the *AFP Premium* exercise yard alone is 1.18 kg NH_3 pl^{-1} a^{-1}. Due to the use of an emission-reducing floor design, this corresponds to a mitigation of 27 % with a 19 % reduction in unroofed walking area compared to the funding conditions. Thus, the emission potential of the *AFP PremiumPLUS* system per animal place and year is lower than that of the *AFP Premium* system as well as that of the *Standard* system. Due to the retrofitting with the mitigation measures, the *StandardPLUS* system achieves the lowest emission potential per animal place and year at 9.85 kg NH_3 pl^{-1} a^{-1}. The NH_3 emission potentials per animal place and year as well as the differences between the individual housing systems are shown graphically in Figure 3. The calculations can be more easily understood with the help of Table 3.

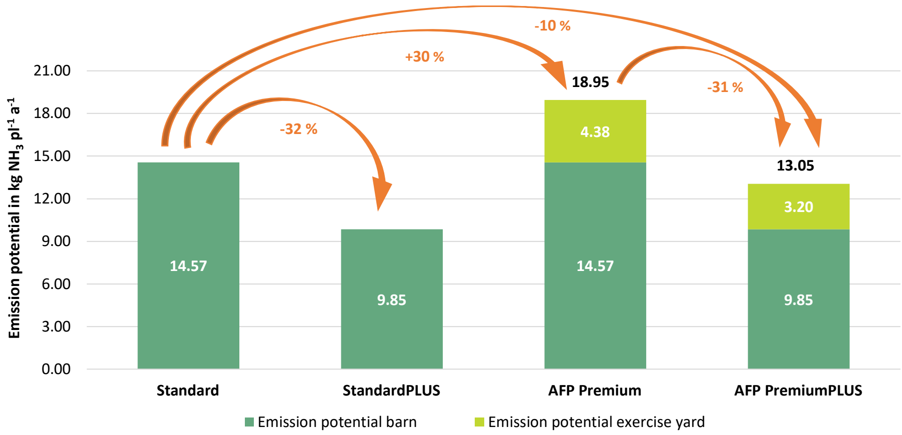

Figure 3: Annual NH_3 emission potential per dairy cow for the evaluated housing systems, divided according to the emissions from the barn and the exercise yard

Table 3: Calculation of the NH_3 emission potential per dairy cow

		Standard	**StandardPLUS**	**AFP Premium**	**AFP PremiumPLUS**
Emission factor barn	kg NH_3 pl^{-1} a^{-1}	14.57	14.57	14.57	14.57
× Mitigation factor “reduction of emitting surfaces”		–	0.845	–	0.845
× Mitigation factor “emission-reducing floor designs”		–	0.8	–	0.8
= Emission potential barn	**kg NH_3 pl^{-1} a^{-1}**	**14.57**	**9.85**	**14.57**	**9.85**
Emission factor exercise yard	g NH_3 m^{-2} d^{-1}	8	8	8	8
× Unroofed walking area	m^2	0	0	248	201
× (1 – 0,5 × mitigation potential “emission-reducing floor designs”)		–	–	–	0.9
× Conversion factor (g → kg; d → a)		0.365	0.365	0.365	0.365
÷ Number of animal places		81	81	165	165
= Emission potential exercise yard	**kg NH_3 pl^{-1} a^{-1}**	**0**	**0**	**4.38**	**3.20**
Emission potential barn	kg NH_3 pl^{-1} a^{-1}	14.57	9.85	14.57	9.85
+ Emission potential exercise yard	kg NH_3 pl^{-1} a^{-1}	0	0	4.38	3.20
= Emission potential per dairy cow	**kg NH_3 pl^{-1} a^{-1}**	**14.57**	**9.85**	**18.95**	**13.05**

Annual total NH_3 emission potential of the dairy cow barn

With an average herd size of 81 dairy cows in the last three years, the total emission potential of the *Standard* system on the example farm was 1180 kg NH_3 a^{-1}. If the emission-reducing floors and elevated feed stalls were retrofitted in this barn, the annual total emission potential would decrease by 32 % to 798 kg NH_3. Without exceeding the total emission potential of the *Standard* system, up to 120 cows could be kept in such a *StandardPLUS* barn with an appropriate extension. This corresponds to an increase of 39 dairy cows (48 %). The annual emission potential per dairy cow in the *AFP Premi-*

umPLUS barn would allow a small herd increase of 9 dairy cows without exceeding the total annual emission potential of the *Standard* barn. The increase of 84 to 165 cows in the EIP project, however, leads to an 83 % (974 kg NH_3) higher total emission potential of 2154 kg NH_3 a^{-1}. The total emission potential of the *AFP Premium* barn would be an additional 973 kg NH_3 (54 %) higher per year. With a total emission potential of 3127 kg NH_3 a^{-1}, the *AFP Premium* barn with a herd size of 165 cows would exceed the total emission potential of the *Standard* barn by 165 % (1947 kg NH_3 a^{-1}). In order to prevent this, a herd size reduction to 62 cows would be necessary. Figure 4 illustrates these correlations.

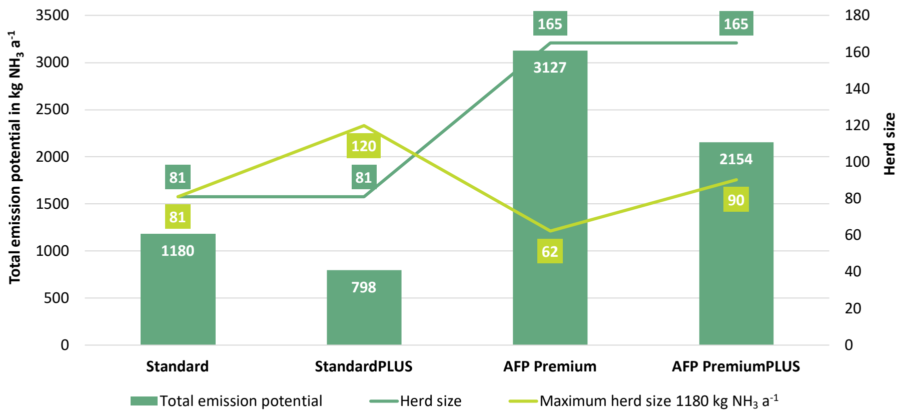

Figure 4: Annual total NH_3 emission potential of the evaluated housing systems depending on the herd size, and the indication of the maximum herd size at which the total emission potential of the *Standard* barn (1180 kg NH_3 a^{-1}) would not be exceeded in the respective system

Investment costs

The net investment costs for the emission-reducing floor design, the alley moistening, the cow shower, the elevated feed stalls and the additional cubicles on the exercise yard amount to 152,567 € for the *AFP PremiumPLUS* barn example. This amount represents the additional costs compared to the *AFP Premium* system. This is 157 € per animal place and kg of NH_3 mitigation. The calculation can be seen in Table 4.

Table 4: Net investment costs of the structural and technical emission mitigation measures including installation for the *AFP PremiumPLUS* barn on the example farm

Total net investment costs for the NH_3 mitigation measures	€	152,567
Number of animal places	n	165
Net investment costs	€ pl^{-1}	925
NH_3 mitigation compared to an *AFP Premium* barn	kg NH_3 pl^{-1} a^{-1}	5.90
Net investment costs	€ pl^{-1} kg NH_3-mitigation^{-1}	157

Discussion

Methodical procedure

The developed method represents a first approach to evaluate a farm's individual NH_3 emission potential when combining several NH_3 mitigation measures in free stall dairy barns. It is characterized by the classification of the mitigation measures into the four categories “reduction of urea excretion in the barn”, “reduction of emitting surfaces”, “emission-reducing floor designs” and “accompanying measures”. The latter occupy a special position, as they do not currently influence the result of the evaluation directly. The other three categories are based on the path taken by nitrogen from feed intake and excretion (“reduction of urea excretion in the barn”) through the size of the area soiled by excrements (“reduction of emitting surfaces”) to the reduction of enzymatic cleavage of the urea on the surfaces by urine drainage (“emission-reducing floor designs”). The multiplication of the mitigation factors proved to be suitable, since it can represent the mutual influence of the mitigation potentials of the individual measures: The mitigation potential of each individual measure decreases as the number of measures used increases. Another advantage of the method is that it is independent of the currently valid emission factors as well as the mitigation potentials of individual measures, so that they can be exchanged at any time as long as they do not change fundamentally (e.g. with regard to the reference to the animal place). In addition, only the basic arithmetic operations are required for evaluation.

There is currently a gap in research with regard to the combined effect of mitigation measures in the field of cattle farming. Therefore, the method proposed here offers potential for the development of a uniform standard that could be transferred to other animal species and production directions. The Netherlands has already taken this step: The procedure for a combination of measures in pig farming according to Annexe 3 of the Dutch Rav List (InfoMil o.J.) is comparable to the method presented here.

The method was developed to evaluate the ammonia emission potentials for Germany based on the emission factors according to VDI 3894-1 (2011). As per KTBL (2013), these form an essential basis for the evaluation of the environmental impact of barn construction projects in approval processes. For dairy cow husbandry, the mitigation potentials in this study tended to be conservative. In the Netherlands, for example, mitigation potentials for floor designs of up to 60 % are stated (Eurich-Menden et al. 2018), whereas a maximum of 20 % was calculated here. The procedure of halving the mitigation potential when using the measures on the exercise yard due to lack of data can also be described as conservative. This prevents an underestimation of the NH_3 emission potential. It is not yet clear how to proceed if several measures of one category with different mitigation potentials are used. In the case of different floor designs within a barn, for instance, the area percentage of a floor design or a different length of stay of the animals in the areas with different floors could be taken into account. This was not relevant for the example barn, because although two different floor designs are used, both of them were considered with the same mitigation potential of 20 %. Thus, it could be calculated with a mitigation factor of 0.8 for the category “emission-reducing floor designs”. Analogous to the mitigation factors, it was planned to also take surcharges into account, for example for larger soiled areas per animal. However, since the emission factor used (VDI 3894-1 2011) is a convention value related to the animal place, which is not based on an area specification, this was not possible. With an area-related emission factor for the cubicle barn, individual barn construction solutions could be better evaluated. Deviations in management could also be taken into account via surcharges and discounts as soon as the corresponding research results are available.

Results of the pilot study

The aim of the EIP Cattle project is to reconcile increased requirements for animal welfare and the reduction of emissions. According to the evaluation, the *AFP PremiumPLUS* barn example can achieve this. The mitigation potential per animal place and year is so high that the additional emission potential from the exercise yard is not only compensated, but the emission factor for the *Standard* cubicle barn is undercut even in the sum of the barn and exercise yard emissions. It should be noted that the emission potentials depend on the management on the individual farm (Wulf et al. 2017) and the emission potentials given here only apply if the alleys are scraped at least 12 times a day with prior alley moistening.

The structuring proved to be a sensible measure to reduce emissions from the exercise yard. In combination with the emission-reducing floor designs, a conclusive concept is obtained with a mitigation potential that could possibly even be higher than calculated in this pilot study. The reason for this is the conservative approach of the mitigation potential. Taking the walking area of the structured yard and thus the emitting surfaces into account instead of multiplying the total area with the emission factor follows the principle that it is not the size of the area that is relevant but its soiled portion (Schrade et al. 2013).

Both the annual emission potential per dairy cow and the total annual emission potential of the free stall dairy barn could be undercut in the *AFP PremiumPLUS* system if the exercise yard is abandoned. This variant then corresponds to a *StandardPLUS* barn, for which the highest mitigation potential was calculated. The lower emission potential of a *StandardPLUS* barn can also be achieved by retrofitting a *Standard* barn. According to the manufacturer, some floor designs are suitable for retrofitting. The problem-free retrofitting of elevated feed stalls could also be confirmed by Benz et al. (2017).

A reduction of the total emission potential of the barn example *AFP PremiumPLUS* could not be shown due to the increased herd size in the new barn, although it is assumed that the emission potential per animal place and year will decrease due to the mitigation measures applied. This shows that, in addition to the emission potential per animal place and year, the herd size is the decisive factor. The structural change characterised by a declining number of dairy farms (Statistisches Landesamt Baden Württemberg 2019) therefore benefits farms that want or have to grow in order to be able to make investments. As long as no higher producer prices can be achieved through a reduction in emissions due to the lack of appropriate seals (Verbraucherzentrale 2019) or label programmes, as would be possible if animal welfare were to be increased (BMEL 2019), it is generally not possible to refrain from increasing or even to reduce the number of livestock in the course of stable construction from a business management point of view.

In this study, the benefits of the additional measures are fully attributed to the reduction of emissions. However, a part of the costs would, in fact, have to be attributed to the increase in animal welfare (Wulf et al. 2011). Synergy effects could for example result through an improvement in claw cleanliness (Schrade et al. 2013, Zähner et al. 2019) and a potentially associated improvement in claw health.

Outlook

The highest mitigation potential was calculated for the *StandardPLUS* system. The potential of the emission mitigation measures could therefore be used particularly effectively, if the mitigation measures were not only applied to new buildings but also to existing buildings. Financial incentives in the form of subsidy programmes, for instance, could contribute to this. In this context, funding would be most desirable for mitigation measures, which contribute to animal welfare and health and can be retrofitted in existing barns. Following the proposed evaluation method, if only 10 % of the almost 328,000 dairy cows in Baden-Württemberg (Statistisches Landesamt Baden Württemberg 2019) were kept in a *StandardPLUS* barn, the emission potential could be reduced by almost 155,000 kg NH_3 a^{-1} compared to keeping all of Baden-Württemberg cows in *Standard* barns. In view of the structural change towards fewer and fewer, but larger farms with overall only a slightly decreasing total number of dairy cows in Baden-Württemberg (Statistisches Landesamt Baden Württemberg 2019), growing farms could also contribute to prevent an increase in environmental impacts in the vicinity of the emission source by means of an "emission-neutral" solution for increasing herd size (Nielinger: personal communication at the expert meeting EIP-Rind on 20.03.2018 in Aulendorf, internal presentation of iMA Richter & Röckle on "N-deposition in licensing practice"). This would be due to the local effect of ammonia (Ministerium für Umwelt, Klima, und Energiewirtschaft Baden-Württemberg 2017). The emission-neutral approach aims to reduce or at most to keep the total NH_3 emissions, despite new constructions or modifications, at the same level through the use of mitigation measures (Nielinger: personal communication at the expert meeting EIP-Rind on 20.03.2018 in Aulendorf, internal presentation of iMA Richter & Röckle on "N-deposition in licensing practice").

In the barns built in the EIP Cattle project further measures with possible emission-reducing properties are used in addition to the measures presented in this pilot study (Testate EIP-RinD o.J.). However, these were not considered in the evaluation, as there is currently a need for research regarding their mitigation potential. These include green roofs, which according to Simon et al. (2018) can reduce the barn temperature by 2–3 °C compared to the outside temperature and shift the temperature peaks back by 2–3 hours, as well as flexible shading devices on the exercise yards. Exercise yards are also used within some multiple-barn housings. According to VDI 3894-1 (2011), these can serve to reduce emissions if the yard is partially roofed.

Conclusion

The approach proposed here for evaluating the ammonia emission potentials of innovative free stall dairy barns when combining several mitigation measures is based on the multiplication of mitigation factors. Due to the logical structure with a conservative approach of the mitigation factors, the method offers potential for the development of a uniform standard, which could be used in practice, for example, to justify the mitigation potential of a combination of measures in approval processes. The use of the method was tested in this pilot study. It was shown that through the construction of appropriately planned free stall dairy barns, the ammonia emission potential per animal place and year could be reduced compared to the *Standard* barn, even if higher animal welfare standards are met (*AFP PremiumPLUS*). The results therefore suggest that the trade-off between emission reduction and animal welfare can be partially resolved by the application of appropriate emission mitigation measures. This is of practical relevance, since synergy effects with respect to animal welfare relativise the high investment costs for the mitigation measures. Nevertheless, the question of future financing of the emission mitigation measures remains to be clarified. This question will presumably not only influence the dissemination of the mitigation measures, but also the herd size development of investing farms and their total emission potential.

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Further information on innovative barn constructions can be found on the homepage of the project EIP Cattle (https://www.eip-rind.de/).