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Abstract

The design of floor surfaces and manure management in dairy cattle houses are crucial factors in reducing ammonia emissions. This study presents data from commercial farms in Baden-Württemberg, Germany. A total of 1445 measurements were carried out on 12 farms with a total of 19 floor types using a dynamic flux chamber. The floor types could be divided into four floor categories: slatted floors, grooved floors, transverse slope floors and paved floors. The farm-by-floor type classification is sparse, however, the installation of more than one floor type per farm allowed comparisons within and between farms. The results showed that all floor categories could achieve comparatively low ammonia concentrations under the given practical conditions, with a high degree of variability in the design of each floor type. As good manure management was standard across all farms, the time since the last manure removal results in non-significant differences in the ammonia concentrations. This suggests that the effectiveness of emission-reducing floor categories depends largely on their specific design and management. This study aimed to compare ammonia concentrations across different floor types under practical conditions using a dynamic flux chamber and to identify differences related to floor type and manure management.

Key words: floor design; ammonia concentrations; dairy cattle barns; manure management.

Introduction

Ammonia emissions from cattle housing represent a major environmental concern (Rychla *et al.*, 2023). Several mitigation strategies have proven effective, including regular alley cleaning, extended grazing, roof insulation, and rapid urine drainage (Bittman *et al.*, 2014; Poteko *et al.*, 2019). Floor configuration plays a key role: transverse slopes reduce surface wetting, while flat floors tend to accumulate manure–urine mixture, increasing emissions (Poteko *et al.*, 2019). Braam *et al.* (1997) showed that floor slope reduces emissions more effectively than increased scraping. Grooved or perforated concrete floors with comb scrapers reduced emissions by up to 46% compared with conventional slatted floors (Swierstra *et al.*, 2001). Structuring feeding areas with elevated feedstalls and dividers yielded additional reductions of 8–19% (Zähner *et al.*, 2020). Further measures include minimizing air exchange between slurry channels and barn air (Bittman *et al.*, 2014) and controlling air temperature, as higher temperatures increase NH_3 release (Poteko *et al.*, 2019).

Challenges in quantifying NH_3 in naturally ventilated dairy barns

Quantifying emissions in livestock buildings remains difficult due to the complexity of air exchange measurements and the influence of environmental conditions, particularly in barns with large side wall openings (Calvet *et al.*, 2013; Takai *et al.*, 2013; Schrade *et al.*, 2011; van Dooren and Mosquera, 2010; Hartje, 2025). Chamber methods provide a practical and cost-effective alternative for short-term comparative measurements, both inside barns and in outdoor settings, and are currently being further optimized. Recent developments of dynamic flux chambers enable reliable NH_3 measurements with good replication and the ability to detect emission mitigation, e.g., after slurry application (Pedersen *et al.*, 2024). However, they only capture partial surfaces, interfere with barn dynamics, and suppress animal activity (Greatorex, 2000). Chambers are divided into static and dynamic types (Schrade *et al.*, 2011): static chambers measure the concentration increase over time in a sealed space, whereas dynamic chambers calculate emissions from concentration differences between inlet and outlet air at a defined airflow rate.

Dynamic flux chambers in application-oriented research

Dynamic flux chambers are widely used to measure ammonia emissions in livestock housing, but methodological differences limit direct comparisons. Chambers vary in size, design, and operational conditions, and some studies supply ultra-high purity Zero Air to remove atmospheric contaminants and determine NH_3 concentration stabilization times. For example, Kang *et al.* (2020) used a Teflon-lined chamber (Ø 40.6 cm, height 17.8 cm) with Zero Air supplied via a mass flow controller; concentrations stabilized after approximately 45 minutes. In contrast, Mosquera *et al.* (2010) and van Dooren and Mosquera (2010) employed a larger chamber (2.37 m × 2.32 m × 0.40 m) with airflow regulated by a fan at 30% capacity, achieving velocities of 0.24–0.26 m/s above the floor.

Evidence from previous studies

Several studies demonstrate the chamber's applicability and sensitivity:

- Mosquera *et al*. (2010): Evaluated new floor designs in cattle barns across multiple locations and days; results showed significant spatial and temporal variation, highlighting the need for repeated measurements.
- Van Dooren and Mosquera (2010): Tested three systems; two modified floors (Systems A and B) and a slurry pit cover (System C). The emission reductions ranged from 39% (System A) to 71% (System C), as compared to the reference floor. The reference floor comprised a concrete slatted floor with slurry pits. System B initially increased emissions (+ 25%), but redesign (slot closure) reduced them by 47%, underscoring the importance of floor design details.
- Mielke *et al*. (2015): Applied a dynamic chamber with photoacoustic analysis in pig yards, treating contaminated areas as point sources. A weak positive correlation with fresh manure was observed, but results underlined the influence of additional factors and the necessity of repeated measurements.
- Winter and Linke (2017): Used a 1 m² chamber designed for laminar airflow to measure cattle yard emissions. They emphasized the importance of dung removal timing and contamination levels for emission mass flow calculations, confirming the method's practicality.
- Pöllinger *et al*. (2015, Emiscrap project): Investigated scraper modifications and frequency. Results showed lower emissions under wet, cold conditions but no clear effect of scraper adjustments.

Synthesis of literature

Overall, dynamic flux chambers have proven versatile and effective for floor-level emission measurements, especially for detecting relative differences between surfaces and management strategies. Their ability to capture point sources within heterogeneous contamination makes them valuable for identifying emission drivers, though repeated and context-specific measurements are essential for reliable estimates (Mielke *et al*., 2015; Winter and Linke, 2017). The objective of the present study was to investigate, under practical conditions in 12 commercial farms, various floor types in the four floor categories of slatted, grooved, transverse sloped, and paved floors with respect to ammonia concentrations using a dynamic flux chamber.

Materials and Methods

Survey data were collected on 12 commercial dairy farms in Baden-Württemberg, southern Germany (Figure 1). The size of herds ranged from 44 to 230 cows, which is indicative of the typical scale of family-run agricultural enterprises in this region.

Baden-Württemberg, covering an area of 35,751 km², is the third-largest federal state in Germany and is home to approximately 5,000 dairy farms with a total of around 300,000 cows. The selected farms were distributed across various geographical regions and climate zones within the state, allowing for a representative assessment of floor types and management practices under diverse practical conditions. Table 1 summarizes key operational data of the 12 farms studied.

At the 12 farms, barns were newly built or renovated between 2018 and 2022 as part of the EIP-AGRI project "Bauen in der Rinderhaltung in Baden-Württemberg," which aimed to combine animal welfare and environmental protection through structural and technical measures while testing their functional reliability.

Farmers focused on reducing ammonia emissions by minimizing soiled, emission-prone surfaces, shortening feces-urine contact time, and ensuring effective cleaning. On eleven farms, feeding areas featured elevated feedstalls with dividers, and manure scrapers operated every two hours on average. One farm with slatted floor (Farm E) used dividers without platforms and a manure removal robot (Lely Discovery Collector, Lely, Netherlands). Two farms (Farm B and Farm C) combined a paved rubber floor (Profikura, Kraiburg Elastik GmbH, Germany) with the Lely Collector manure removal robot (P5 Profikura combined with Collector). A cleaning robot was also in use at Farm F. This was the JOZ Barn E model (JOZ, Netherlands), which cleaned a paved rubber floor (Kura, Kraiburg Elastik GmbH, Germany) at this farm (P3 Kura combined with Barn E).

Emission-reducing rubber flooring was installed at least in the feeding alleys on eleven farms, and one farm (Farm I) used automated straw distribution. Nine farms employed automatic milking systems, with Farm E switching from parlor milking during the study.

There were 19 different floor types, which were subdivided into the four floor categories of slatted floor (S), grooved floor (G), transverse slope (T) and paved floor (P) and also had different surface profiles (Table 2). Between two and four floor types were installed in each of the farms (Table 3).

Dynamic flux chamber design

The dynamic flux chamber for measuring ammonia concentrations on different floor surfaces was designed based on the Association of German Engineers (Verein Deutscher Ingenieure - VDI) guideline no. 3475, sheet 1 of 2018, according to Mielke *et al*. (2015) and Winter and Linke (2017). The development of this chamber was originally initiated for the purpose of conducting odour measurements, with a particular focus on biofilters. The chamber described in the guideline has a base area of 1 m², which can be enlarged to 4 m², and is flush with the ground to prevent wind from blowing into it. The flow rate is measured using an exhaust gas nozzle with a speed-controlled fan. The self-constructed dynamic flux chamber consisted of a plastic measuring chamber with a volume of 70 l and a base area of 0.5 m², which led into a 100 mm pipe with a fan (Hon and Guan, Shenzhen, China) with an output of 165 m³/h. The objective in the design of the flux chamber was to minimise the environmental influences on the outgassing of ammonia during a concentration measurement. At the same time, influencing parameters such as air velocity and temperature were recorded or stabilised using the measuring chamber method. In contrast to the flux chamber described for biofilter materials, the flux chamber for use on predominantly solid floors was not sealed at the base, but stood 1.5 cm elevated on feet. The all-round open edge ensures uniform flow through the flux chamber, where a vacuum is created at the top by the tube fan. The measuring device can therefore be described as an open dynamic flux chamber, similar to the measuring device used by Mosquera *et al*. (2010) and van Dooren and Mosquera (2010). The dimensions of the flux chamber and the separation of the measuring unit and the dynamic flux chamber increased its mobility and allowed frequent changes of the measuring point in the stable (Figure 2).

The multi-gas-monitor M.A.C. 2240 (ppm Messtechnik, Forstinning, Germany) was used to measure the ammonia concentrations. Its measuring principle is based on infrared photoacoustics. An infrared radiation source emits infrared radiation (IR radiation) over a broad wavelength range. Special optical filters allow only certain wavelengths with a narrow bandwidth to pass through from the spectrum of the radiation source. Each of these wavelengths is characteristic of the gas components to be determined. The gas components absorb the IR radiation at these specific wavelengths. The sensor converts this effect into electrical signals. The measurement consisted of a purging process of about five seconds, followed by a waiting period of about three seconds to stabilise the gas in the measuring cell, and finally the actual measurement, in which the mean value was calculated from several individual measurements. Each measurement took 20 seconds.

Several measurements were carried out in succession at the same location and combined into 5-minute mean values within the device. This avoids misinterpretations due to short-term concentration fluctuations. The gas monitor had three measuring points M1, M2 and M3, which changed automatically after five minutes and an average value calculation per measuring point. The three consecutive 5-minute mean values formed a measuring cycle. Measurement points were fixed for each farm and documented in detailed measurement protocols, ensuring consistency across all measurement sessions.

Two measuring points M1 and M2 were located in the PVC pipe below the pipe fan. Therefore, M1 and M2 were identically coded for data evaluation, whereby a common mean value was then estimated in the analysis. The third measuring point M3 was installed on the outside of the flux chamber 30 cm above the floor. The background concentration was measured for control purposes. Due to the special situation in the stables, where several different floor types were present, the stable air was influenced by the emissions from the different floor types and therefore did not represent a meaningful reference value for a balance with the measured values from the dynamic flux chamber. Therefore, M3 values were not substracted from M1/M2 values prior analysis. Additionally, results on M3 values were not presented here. However, M3 values were included in the calculation to increase precision. To reach this, separate means for M1/M2 and M3 were estimated, but block effects as well as block and error variances were estimated using all data of M1, M2 and M3. With a concentration of 1.67 ppm (SD 1.57 ppm), the average value for M3 was low compared to the mean value of 6.2 ppm for M1 and M2.

The device was specified for an ambient temperature range of + 10°C to + 40°C. The instrument operates over a measurement range of 0.4–500 ppm NH_3 with a resolution of 0.1 ppm. The measured values were multiplied by a factor of 0.76 to convert from ppm to mg/m³. Before beginning a new measurement day, the instrument was restarted directly in front of the barn, triggering an automatic calibration routine. This included a self-test, heating of the measuring chamber to approximately 50°C, and an automatic zero adjustment using ambient air passed through an activated carbon filter. The zero point was checked across all measuring ranges and accepted only if consecutive values met the tolerance limits; otherwise, the cycle was repeated, or a fault was indicated. This procedure ensured that all measurements began with a stable and drift-free baseline.

The floor surface temperature was measured using a laser thermometer (PCE-777N, PCE Deutschland GmbH Prüfgeräte, Meschede, Germany) and the temperature in the flux chamber was measured ten centimetres above the ground using a thermo data logger (LOG32TH, Dostmann, Reicholzheim, Germany). The air pressure directly above the floor surface was on average 950.3 mbar (SD 8.25, CV 0.01, median 951.1, *n* = 1092 5-minute mean values). Measurements were always taken in the stable temperature range between 15 and 25 °C. Furthermore, the air velocity was measured during the measurements using a thermoanemometer (testo 405i, Testo, Lenzkirch, Germany) either in the PVC pipe below the tube fan at the level of the two measuring points M1 and M2 (610 measured values) or above

the floor surface (1146 measured values). The value measured close to the floor was used to determine the wind speed and was thus not used to calculate the air volume flow. The duct fan generated a defined air flow with a wind speed of 4.57 m/s (SD 0.32, CV 0.07, maximum 5.24, minimum 4.0, median 4.53 m/s, *n*=610 5-minute mean values) in the area of measuring points M1 and M2. Directly above the floor surface inside the flux chamber, the wind speed was on average 0.61 m/s (SD 0.25, VK 0.41, maximum 1.27, minimum 0.12, median 0.62, *n*=1146 5-minute averages), which is consistent with air velocities reported at cow level in commercial dairy barns (Reuscher *et al*., 2024; Mondaca *et al*., 2019, Fiedler *et al*., 2013).
The air flow rate of 129.2 $m^3 h^{-1}$ was calculated from the wind speed and the cross-sectional area of the PVC pipe (0.79 cm^2).
At each measurement, the emission mass flow F_NH_3 was calculated from the ammonia concentration C_NH3 and the air flow rate Q according to Winter and Linke (2017):

$$F_{NH3} = C_{NH3} \cdot Q$$

where F_{NH3} is the emission mass flow in mg/h, C_{NH3} is the measured ammonia concentration in mg/m^3, and Q is the volumetric airflow through the measurement system.
The airflow rate Q was calculated from the measured air velocity and the tube diameter:

$$Q = v \cdot A$$

where v = 4.57 m/s is the air velocity and A is the cross-sectional area of the tube (d = 0.1 m):

$$A = \pi \cdot (d^2 / 4) \approx \pi \cdot (0.1^2 / 4) \approx 0.00785 \text{ m}^2$$

$$Q = 4.57 \text{ m/s} \cdot 0.00785 \text{ m}^2 \approx 0.0359 \text{ m}^3/\text{s} \approx 129 \text{ m}^3/\text{h}$$

Thus, the volumetric airflow through the tube with the fan resulted in 129 m^3/h.
Between 1 and 5 measurement dates took place at each of the 12 study farms in the period from 3 July 2020 to 26 September 2022. A total of 34 measurement dates were conducted (Table 4). At each measurement date, several measurement cycles occurred. After each measurement cycle of 15 minutes (5 minutes of M1, 5 minutes of M2 and 5 minutes of M3), the location (measurement point), or rather the floor type, was changed in a randomised sequence.

Manure management on the farms

Under the practical conditions in the study, neither the clearliness, nor the time since last cleaning was measured. However, a pollution assessment of the sampling point was carried out in four categories (Table 5) and considered in the evaluations. Different stationary scraper-type dung removal systems and two different dung removal robots on a paved floor were used on the farms. The stationary dung removal systems usually ran every one to two hours. The dung removal robots were the Barn E model (JOZ, Westwoud, Netherlands), which collected the excrement using a rotating roller, and the Collector model (LELY, Maassluis, Netherlands), which had a suction device and simultaneously moistened the floor using a spraying device.

Data analysis

A total of 1445 5-minutes measurement mean values (including M1, M2 and M3) from 12 farms across 34 measurement dates were analysed using a mixed model. The model can be described as:

$$y_{ijklmnop} = \mu + \tau_i + \varphi_{ij} + \omega_k + (\tau\varphi)_{ij} + (\tau\omega)_{ik} + (\varphi\omega)_{jk} + (\tau\varphi\omega)_{ijk} + \beta t_{ijklmnop} + x_p + f_l + d_{lm} + c_{lmn} + e_{ijklmnop}$$

where $y_{ijklmnop}$ is the o-th 5-minutes measurement mean value at measurement cycle n at farm l and day m on stable floor j from category i, μ is the intercept, τ_i, φ_{ij}, and ω_k are the fixed main effects of category i, floor type j within category i and measurement point k, $(\tau\varphi)_{ij}$, $(\tau\omega)_{ik}$, $(\varphi\omega)_{jk}$, and $(\tau\varphi\omega)_{ijk}$ are the two- and three-way interaction effects of the corresponding main effects, respectively, β is the slope of the temperature of the stable $t_{ijklmnop}$, x_p is the effect of p-th rating of dirtiness, f_l, d_{lm}, and c_{lmn} are the random effects of farm l, day m within farm l and measurement cycle n within day m. The latter three effects accounted for the sampling structure of the data. The effect $e_{ijklmnop}$ is the error of $y_{ijklmnop}$ with a measurement specific variance. A first order autocorrelation with heterogeneous variances was assumed for the measurements mean values from M1 to M3 within a measurement cycle. Furthermore, a first order autocorrelation was fitted across measurement cycles within a measurement date. In both cases, the autocorrelation accounts for potential temporal correlations. To fulfil pre-requirements of homogeneous variance and normal distribution, data were logarithmically transformed prior to analysis. Note that the detection limit of the multi-gas-monitor was set to 0.4 ppm. Therefore, values below this value were set to 50% of the detection limit. Note that three variables of temperature were available (floor surface temperature, temperature in the flux chamber, air temperature in the pipe). However, temperature values were highly correlated. Therefore, the most predictable temperature was used throughout all analysis.

In case of significant F tests, means within a category were compared via Fishers LSD test and results of multiple comparisons were presented as letter display. Means were adjusted for temperature of the stable floor. Note that means were not adjusted for urea content available from LKV Baden-Württemberg or two temperature measurements, one in the flux chamber and one on the floor surface. The reason was that these covariates were not significant after accounting for the temperature of the stable floor.

Results

On average, grooved floors had the lowest and slatted floors the highest values of ammonia emmisions of the four floor categories (Figure 3). The analyses showed that the rating of dirtiness categories ‘clean + dry’, ‘clean + moist’, ‘contaminated + dry’ and ‘contaminated + moist’ had no significant influence on the individual results (p=0.163) with nearly similar means for categories ‘clean and dry’ (6.03 ppm) and ‘contaminated’ (6.09 ppm). Pairwise comparison of .floor types is shown in Table 6.

Within the four floor categories, there were a large number of types, which arose from different structural-technical designs, installation with a slope, stationary or fully automatic dung removal technology and the use of humidification technology. This can be illustrated by the ranking of the 19 floor types (Figure 4). The floor type with the lowest values was a grooved floor, followed by a slatted floor and three sloping floor types. The large differences in the floor types within a floor category did not allow any generalised statement to be made about the floor categories. Overall, the 50% of floor types below the overall average included one slatted floor, two grooved floors, three transverse sloped floors and three paved floors. Thus, 17% (1/6) of the slatted floor types were within the lower half of the overall average, compared with 67% (2/3) for grooved floors and 60% (3/5) for transverse sloped floors and paved floors, respectively.

Slatted floors

Within the different types of slatted floor, the values for the slatted floor S_Profikura 2% slope were at the lowest level and differed significantly from all other types (Figure 5).

The slatted floor S_Profikura without slope showed the highest values compared to the other types and thus differed significantly from almost all slatted floor types, with the exception of the slatted floor type S_Easyfix. There were no significant differences between the two rubber mats KURA SB and KURA S and the slatted concrete floor (S_Concrete) and slatted floor Easyfix (S_Easyfix).

Grooved floors

There were significant differences between all three types of the grooved floors (Figure 6). The values for the concrete grooved floor were at the lowest level.

Transverse slope floors

Among the four types for transverse slope floors, the types T_Diamond-patterned floor, T_Profikura 3D and T_Profikura did not differ from each other (Figure 7). The T_V-Twin flooring was significantly better than the other transverse floor types, although this did not apply to the T_V-Twin type without drain. This only differed from the T_Diamond-patterned floor type. T_V-Twin with and without a drain did not differ significantly from each other.

Paved floor types

Two of the paved floors had cross passageways that were cleaned manually. These are marked with a black frame. Two other variants were cleaned with manure robots and are marked with a red frame. The highest values were measured on the P_Kura floors with Barn E, the collecting manure robot, and on P_Concrete (Figure 8).

Discussion

This study was conducted on 12 commercial dairy farms that were part of a project specifically aimed at reducing ammonia emissions. The farms implemented a combination of mitigation measures, including optimized floor designs, frequent and automated manure removal, humidification systems, and elevated feeding stalls, with particular attention to cleanliness and maintenance. As a result, the measured ammonia concentrations reflect not only the influence of floor type, but also the cumulative effect of these technical measures and high-standard management practices. While this limits the direct transferability of absolute values to other farms, the study provides valuable insights into the relative performance of different floor types under practical conditions and highlights the critical role of management in achieving effective emission reduction.

Suitability and limitations of the dynamic flux chamber

The dynamic flux chamber is generally suitable for internal comparisons of floor types and their cleaning methods (Mosquera *et al*., 2010; van Dooren and Mosquera 2010; Mielke *et al*., 2015; Pöllinger *et al*., 2015; Winter and Linke, 2017). However, it does not allow conclusions to be drawn about absolute emissions, as there is no flow model and emissions are artificially generated by active air extraction.

The dynamic flux chamber used in this study covered 0.5 m² of floor surface. This is smaller than in other studies using dynamic flux chambers (Mosquera *et al*., 2010; van Dooren and Mosquera, 2010), but larger than the 0.13 m² surface used by Kang *et al*. (2020). The chamber was designed to be practical under real on-farm conditions, including multiple floor types, numerous farms, and repeated measurements (1,445 measurements over 34 measurement dates on 12 farms with 19 floor types). The design balanced manageable size, mobility, and ease of operation while allowing representative measurements across different floors. Unlike Kang *et al*. (2020), no external zero gas was supplied, and no stabilization time for concentrations inside the chamber was considered.

Instead, a stable airflow of 0.61 m/s was maintained directly above the floor surface inside the flux chamber, reflecting typical air velocities reported for commercial dairy barns (Reuscher *et al*., 2024; Mondaca *et al*., 2019; Fiedler *et al*., 2013).

Slatted floors represent a special case, as air intake from the slurry pit may affect emission readings. Nevertheless, internal comparisons among slatted floor types were not affected. The air extraction created a relatively stable dilution at the sampling point (CV = 0.07). Turbulence near the floor caused by the 1.5 cm gap between the chamber edge and floor resulted in higher variability in wind speed at floor level (CV = 0.40), but airflow at the measurement point remained consistent.

Stable airflow conditions may have influenced ammonia concentrations differently across floor types. However, this is assumed to introduce only a systematic bias that does not compromise relative comparisons. Each barn contained multiple floor types, so overall barn air was influenced by all surfaces. Given the low average ammonia concentration in barn air (M3 = 1.67 ppm, SD = 1.57 ppm), this systematic bias was accepted rather than subtracting barn air values from flux chamber measurements, as done in Mosquera *et al*. (2010) and van Dooren and Mosquera (2010).

Impact of floor contamination

Previous studies have shown no significant difference in NH_3 concentrations between soiled and freshly cleaned walking surfaces (Pöllinger *et al*. 2015; Winter and Linke, 2017), which is confirmed by this study. However, the farms analysed in this study consisted of newly built barns with high standards of floor hygiene. Farmers were aware of the problem and had technical equipment for thorough and frequent cleaning. For example, elevated feeding stalls were commonly installed in feeding alleys, allowing high frequency cleaning without disturbing the feeding animals (Benz *et al*. 2014). In addition, humidification devices were present either in the rear curb of the cubicles, along the upstands of the elevated feedstalls or directly at the manure removal robot.

The exception was the T_V-Twin floor type, which had only recently been installed. According to the farm manager, the manure scraper had not yet been fully optimised, which explains the slightly higher NH_3 values compared to the other tranverse sloped floor types. This also helps to explain why, in contrast to previous research (Schrade *et al*., 2017), the transverse sloped floor type did not perform better on average than the paved floor type in this study.

Classification of floor categories

Among the four floor categories, grooved floors had the lowest NH3 values, significantly differing from all other floors. This finding is particularly relevant for practical applications, as grooved floors—when implemented as rubber mats with an appropriate profile—can be easily retrofitted in existing barns. The adaptation of manure removal technology, specifically the implementation of scraper lips with a comb profile, was likely successful, leading to low ammonia concentrations.

Within the slatted floor category, the S_Profikura slatted floor type showed the highest NH3 values when installed flat but the lowest when installed with a 2% slope. This suggests that floor slopes may contribute to lower ammonia concentrations in slatted floors. However, these measurements were conducted on only one farm without replication, preventing definitive conclusions.

The unexpectedly low NH3 levels observed for the grooved concrete floor are noteworthy, as no specific adaptations to the manure removal technology (e.g., comb-like rubber scraping lips on scraper flaps) were made for this floor type. However, this floor also featured a cross slope of approximately 2%. While cross slopes are generally considered most effective for urine drainage at a 3% gradient (Steiner *et al*., 2012), it is possible that even a 2% slope had a positive effect. A similar trend was observed in the slatted floor with an additional 2% slope, which also showed particularly low NH3 values. Since these floor types were only present on one farm, further investigations on additional farms with repeated measurements are necessary to validate these findings.

Building on these observations, it remains to be determined whether slopes greater than 3% might be more effective for wider alleys with cross slopes. Contrary to previous studies (Braam *et al*., 1997), sloping floors did not show significant differences from paved floors. The measurements on paved floors did not differentiate between alleyways and crossways, although floor contamination was recorded and considered. As a result, the source of variability within paved floor types remains unclear.

Among paved floors using different manure removal robots, it was notable that vacuum-based manure removal outperformed collection-based manure removal. However, floor types and humidification technologies varied, and each system was only available on one farm. The observed differences between these manure removal methods warrant further investigation.

The impact of floor surface profiling on ammonia concentrations could not be conclusively determined from this study, as measurements were conducted under practical conditions. The heterogeneity of results suggests that other factors—such as cleaning management, humidification technology, manure removal technology, or floor slopes—had the greatest influence on ammonia concentrations.

Conclusions

Measurements on 12 farms revealed a wide range of NH_3 emission mass flow, from 0.20 to 0.99 mg/h across all floor types except slatted floors, which could only be compared internally due to air intake from the slurry cellar. The results highlight the potential of floors to reduce ammonia emissions under optimal management. On these farms, combined mitigation measures—including adapted manure removal technology, humidification systems, and elevated feed stalls enabling frequent cleaning—contributed to low NH_3 values. Transverse slope and grooved floors showed particularly low emissions, while slatted and paved floors also achieved good results depending on their design. Although dynamic flux chamber measurements under practical conditions do not allow precise quantification of absolute emissions, they provide robust insights into relative differences between floor types and demonstrate that management plays a critical role in achieving emission reductions. The study's findings are specific to farms implementing multiple mitigation measures and high hygiene standards, and thus should be interpreted with caution when generalizing to other settings.

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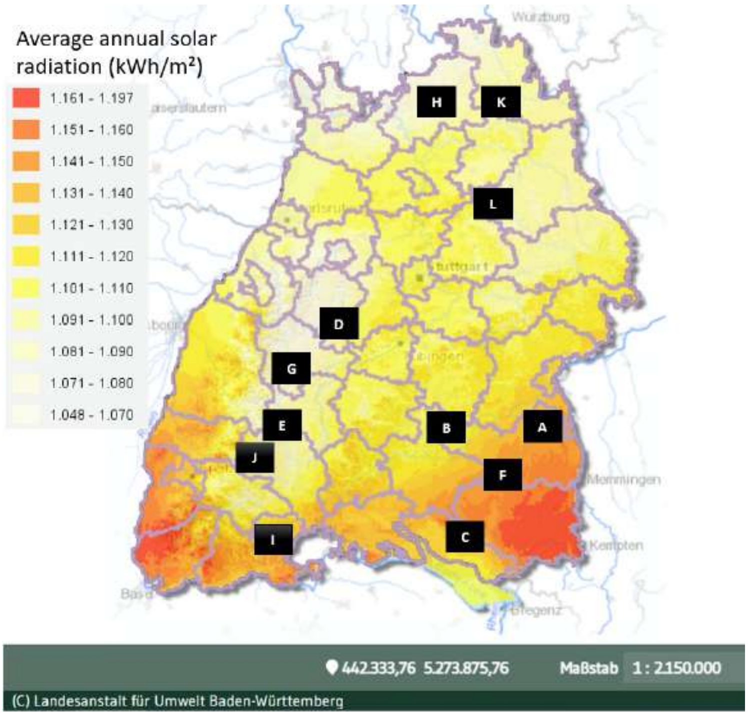

Figure 1. Distribution of sampled farms across the whole of Baden-Württemberg in different geographical regions and climate zones.

Figure 2. Dynamic flux chamber with multi-gas monitor in a plastic box.

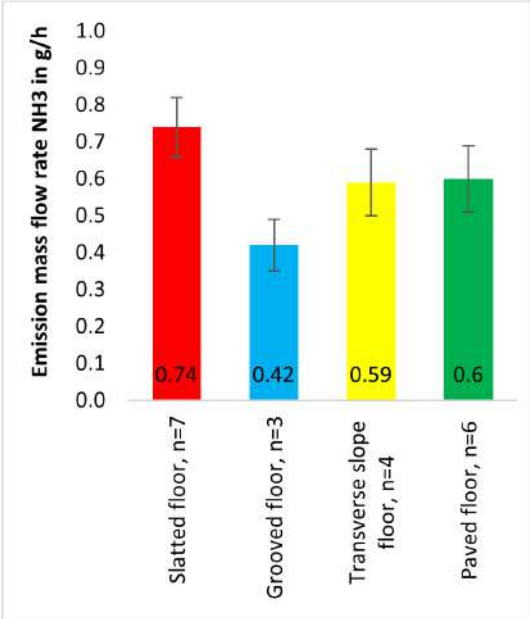

Figure 3. Comparison of the four floor categories with a total of 19 floor types on 12 farms, 1445 measurements. n, number of farms.

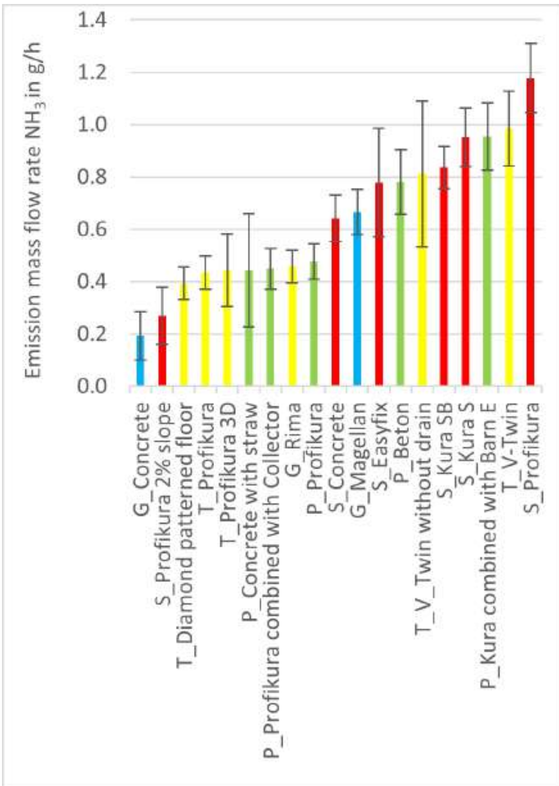

Figure 4. Emission mass flow rate of all 19 floor types with ascending values from left to right, slatted floor types in red, grooved floor types in blue, transverse sloped floor types in yellow, paved floor types in green.

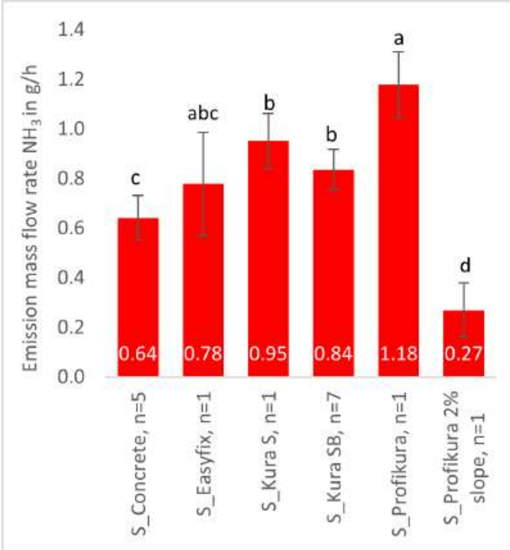

Figure 5. Comparison of the six types of slatted floor on ten farms. n, number of farms, bars with at least one identical letter indicates non-significant differences between means.

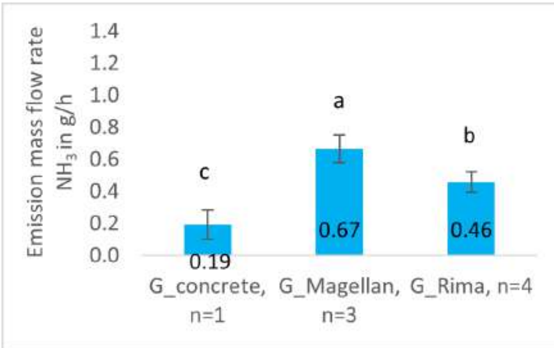

Figure 6. Comparison of the three grooved floors on six farms. n, number of farms, bars with at least one identical letter indicates non-significant differences between means.

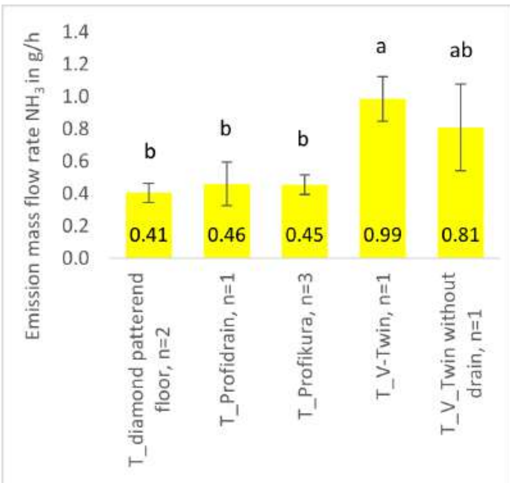

Figure 7. Comparison of the five transverse slope floors on five farms. n, number of farms, bars with at least one identical letter indicates non-significant differences between means.

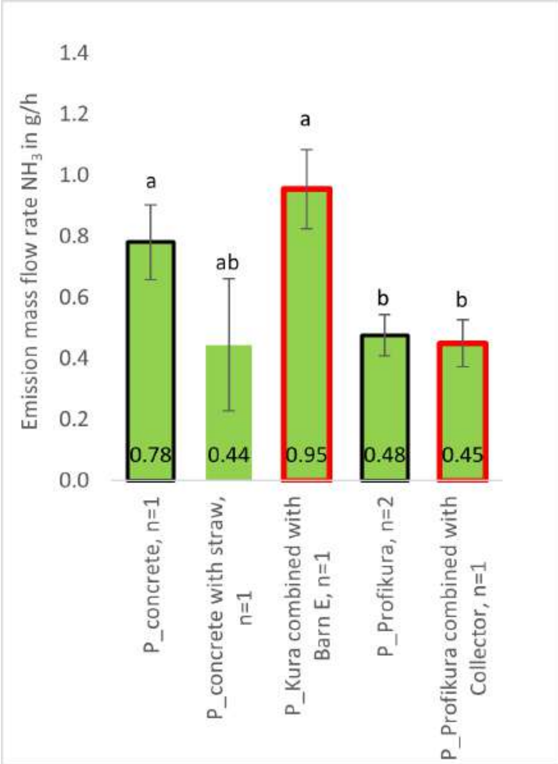

Figure 8. Comparison of the paved floor types. Black frame, installation on a cross-aisle; red frame, cleaning with a manure removal robot; n, number of farms, bars with at least one identical letter indicates non-significant differences between means.

Table 1. Key operational data of the 12 farms.

Farm	Herd size	Milking system	Breeds	Annual milk yield (kg)	Total walking area (m^2)	Space per cow (m^2/cow)
E	44	AMS	BV, VW*	6100	247	6.5
I	62	P	FL	4900	539	9.3
J	72	AMS	VW	7500	281	3.9
A	144	AMS	SBT, RBT, FL*	9500	791	11.8
B	163	AMS	SBT, FL*	11500	898	6.6
D	188	AMS	FL	11200	974	5.9
F	146	AMS	SBT, RBT	10300	1203	9.4
G	150	AMS	SBT, RBT, FL*	9900	624	5.2
K	230	P	FL*	8100	1097	5.9
L	148	AMS	FL	11000	710	7.4
H	210	P	SBT, RBT, FL*	8700	1125	6.3
C	180	AMS	SBT, FL*	9700	504	7.0

AMS, automatic; P, parlor; *also crossbred animals.

Table 2. Floor categories and floor types (illustrations are examples, not to scale); not shown slatted floor ProfiKura S 2% slope, transverse slope V-Twin without drain.

Slatted floor (S)	Grooved floor (G)	Transverse slope floor (T)	Paved floor (P)
			
S1 Concrete	G1 Concrete	T1 Diamond-patterned floor	P1 Diamond-patterned-floor
			
S2 Easyfix	G2 Magellan	T2 Profikura 3D	P2 Concrete with straw
			
S3 Kura S	G3 Rima	T3 Profikura	P3 Kura combined with Barn E
			
S4 Kura SB		T4 V-Twin	P4 Profikura
			
S5 Profikura			P5 Profikura combined with Collector

Table 3. Floor plans and floor types on the 12 farms.

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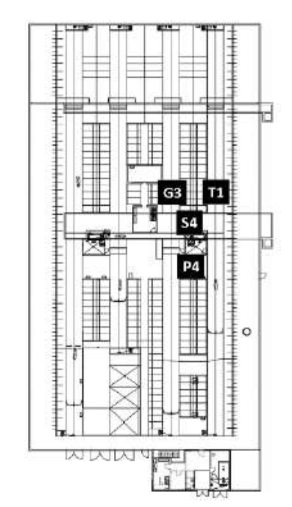
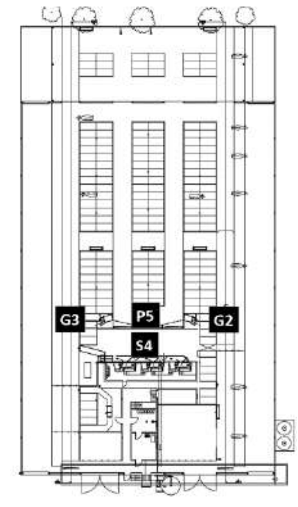
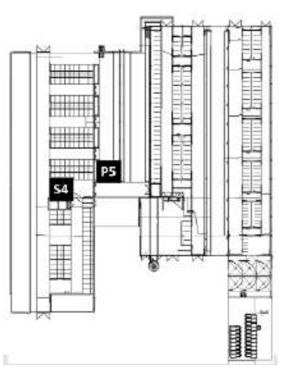
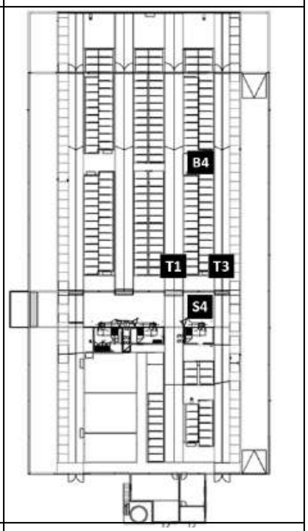
<td></td>
<td></td>
<td></td>
<td></td>
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<tr><th>E</th><th>F</th><th>G</th><th>H</th></tr>
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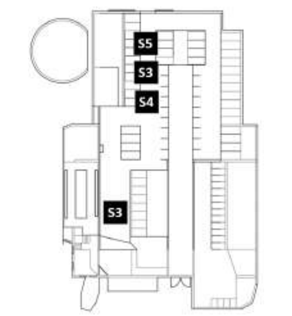
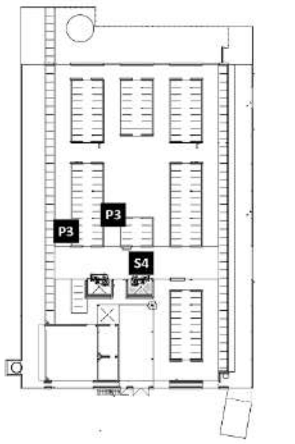
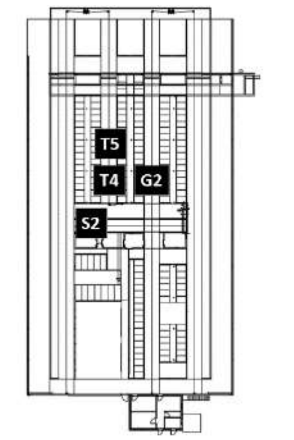
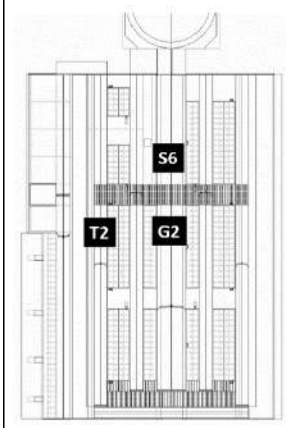
<td></td>
<td></td>
<td></td>
<td></td>
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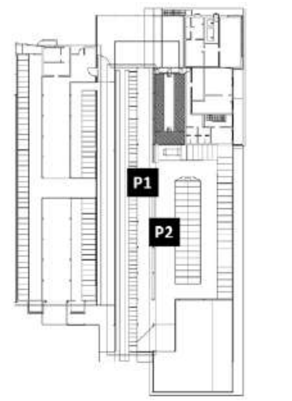
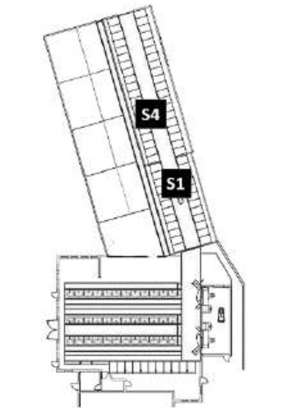
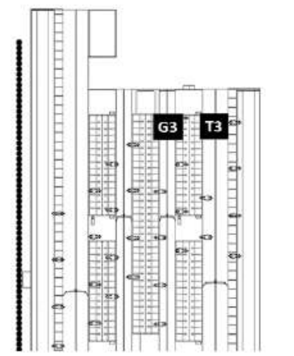
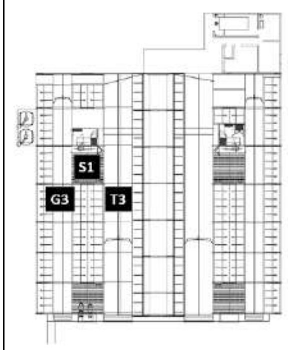
<td></td>
<td></td>
<td></td>
<td></td>
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Slatted floor		**Grooved floor**		**Transverse slope floor**		**Paved floor**	
S1	Concrete	**G1**	Concrete	**T1**	Diamond-patterned floor	**P1**	Diamond-patterned floor
S2	Easyfix	**G2**	Magellan	**T2**	Profikura 3D	**P2**	Beton with straw
S3	Kura S	**G3**	Rima	**T3**	Profikura	**P3**	Kura combined with Barn E
S4	Kura SB			**T4**	V-Twin	**P4**	Profikura

S5	Profikura			**T5**	V-Twin without drain	**P5**	Profikura combined with Collector
S6	Profikura S 2% slope						

Table 4. Number and date of measurement dates on the farms.

Farm	Number and dates of measurements				
	1	2	3	4	5
A	11.9.20	1.6.21	20.10.21	3.8.22	
B	3.7.20	3.9.20	3.6.21		
C	14.9.20	2.6.21	8.8.22		
D	17.9.20	8.7.21	15.9.21	26.9.22	
E	22.4.20	20.5.20	9.9.20	6.7.21	7.7.21
F	8.6.22	23.9.22			
G	10.6.22	1.8.22			
H	21.9.22				
I	7.9.21	8.9.21	31.10.21	10.8.22	
J	8.9.20				
K	22.9.20	13.7.22			
L	23.9.20	16.9.21	14.7.22		

Table 5. Categories of floor pollution.

Pollution category			
Clean + dry	Clean + moist	Dirty + dry	Dirty + moist
			

Table 6. *P*-values for the test of differences between floor type means against zero. Only pairs within a floor category are compared.

Floor type		Mean difference	*p*-value
S_Easyfix	S_Concrete	0.2600	0.4830
S_Easyfix	S_Kura SB	-0.1013	0.7804
S_Easyfix	S_Kura S	-0.2966	0.4395
S_Easyfix	S_Profikura	-0.6471	0.0967
S_Easyfix	S_Profikura 2% slope	1.1578	0.0121
S_Concrete	S_Kura SB	-0.3613	0.0082
S_Concrete	S_Kura S	-0.5566	0.0026
S_Concrete	S_Profikura	-0.9070	<0.0001
S_Concrete	S_Profikura 2% slope	0.8978	0.0077
S_Kura SB	S_Kura S	-0.1953	0.1389
S_Kura SB	S_Profikura	-0.5458	0.0002
S_Kura SB	S_Profikura 2% slope	1.2591	<0.0001
S_Kura S	S_Profikura	-0.3504	0.0195
S_Kura S	S_Profikura 2% slope	1.4544	<0.0001
S_Profikura	S_Profikura 2% slope	1.8049	<0.0001
G_Concrete	G_Magellan	-1.2021	<0.0001
G_Concrete	G_Rima	-0.7587	0.0176
G_Magellan	G_Rima	0.4434	0.0006
T_Profikura 3D	T_Diamond patterned floor	0.1246	0.7035
T_Profikura 3D	T_Profikura	0.02273	0.9442
T_Profikura 3D	T_V-Twin	-1.0409	0.0029
T_Profikura 3D	T_V_Twin without drain	-0.7492	0.1829
T_Diamond patterned floor	T_Profikura 3D	-0.1019	0.3690
T_Diamond patterned floor	T_V-Twin	-1.1655	<.0001
T_Diamond patterned floor	T_V_Twin without drain	-0.8738	0.0751
T_Profikura	T_V-Twin	-1.0636	<0.0001
T_Profikura	T_V_Twin without drain	-0.7719	0.1144
T_V-Twin	T_V_Twin without drain	0.2916	0.5499
P_Concrete with straw	P_Concrete	-0.6927	0.1446
P_Concrete with straw	P_Profikura	-0.07532	0.8823
P_Concrete with straw	P_Kura combined with Barn E	-0.9915	0.0662
P_Concrete with straw	P_Profikura combined with Collector	-0.01247	0.9811
P_Beton	P_Profikura	0.6173	0.0017
P_Beton	P_Kura combined with Barn E	-0.2989	0.2579
P_Beton	P_Profikura combined with Collector	0.6802	0.0048

P_Profikura	P_Kura combined with Barn E	-0.9162	<0.0001
P_Profikura	P_Profikura combined with Collector	0.06286	0.6972
P_Kura combined with Barn E	P_Profikura combined with Collector	0.9791	<0.0001