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Author(s):
Poteko, Jernej; Zähner, Michael; Steiner, Beat; Schrade, Sabine

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Research Paper

Residual soiling mass after dung removal in dairy loose housings: Effect of scraping tool, floor type, dung removal frequency and season

Jernej Poteko [a,b], *Michael Zähner* [a], *Beat Steiner* [c], *Sabine Schrade* [a,*]

[a] *Agroscope, Animal Production Systems and Animal Health, Taenikon, 8356 Ettenhausen, Switzerland*
[b] *Animal Nutrition, Department of Environmental System Sciences, ETH Zürich, 8092 Zürich, Switzerland*
[c] *Agroscope, Research Division Competitiveness and System Evaluation, Taenikon, 8356 Ettenhausen, Switzerland*

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Clean floors in dairy housing have a positive impact on claw health, cleanliness of the animals and ammonia-emission reduction. Key indicator of cleaning quality is residual soiling mass, i.e. the manure remaining on the floor after dung removal. The aim of this study was to show the effects of scraping tool, rubber mat type, solid floor type, dung removal frequency and season on residual soiling mass. The comparison two scraping tools and two rubber mat types in winter showed that the rubber mat type ($p = 0.001$) and the scraping tool ($p = 0.001$) influenced the residual soiling mass. The cleaning quality was better on the common than on the soft rubber mat and the hard rubber lip left less residual soiling mass versus the metal blade (means: 174 vs. 230 g m^{-2} on common; 230 vs. 243 g m^{-2} on soft rubber mat). Further two floor types (with and without 3% slope) and two dung removal frequencies (three and 12 times per day) were investigated in three seasons. The statistical analysis proved the season as significant ($p < 0.001$). Residual soiling mass in winter was smaller than in warmer seasons regardless of floor type and dung removal frequency. Within the summer dataset the floor type was significant ($p = 0.037$): the floor without slope showed less residual soiling mass in average 218 resp. 234 g m^{-2} with three resp. 12 dung removal events per day than the sloped floor with 280 resp. 303 g m^{-2}.

1. Introduction

Dung removal represents an important procedure in the daily operation in dairy housings and includes scraping off faeces, urine and other waste from floor surfaces (Fulhage, 1997). Clean floor surfaces have a positive influence on claw health (Somers, Frankena, Noordhuizen-Stassen, & Metz, 2005) and contribute to a reduction in ammonia emission (Braam, Ketelaars, & Smits, 1997; Braam, Smits, Gunnink, & Swierstra, 1997; Snoek, Stigter, Blaauw, Groot Koerkamp, & Ogink, 2017; Swierstra, Smits, & Kroodsma, 1995). Thus, achieving a good cleaning quality by improving the dung removal efficiency is necessary.

Various aspects should be considered in the context of cleaning quality. Dung removal in dairy housings with solid

* *Corresponding author*. Agroscope, Animal Production Systems and Animal Health, Taenikon 1, CH-8356 Ettenhausen, Switzerland.
E-mail address: sabine.schrade@agroscope.admin.ch (S. Schrade).
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floors is performed with various technical systems (Pöllinger, 2001; Steiner & Keck, 2000). These systems differ not only in design and shape but also in materials of the scraping tools, which are in direct contact with the floor surface (Buck et al., 2013). Scraping tools in dairy housings are often equipped with a metal blade (Schrade, Steiner, & Keck, 2013). To improve cleaning quality, manufacturers recommend various rubber lips or brushes, especially when combined with rubber mats.

Floor surfaces equipped with rubber mats have a beneficial effect on cow comfort during standing and walking (Telezhenko, Lidfors, & Bergsten, 2007) and claw health (Vanegas, Overton, Berry, & Sischo, 2006), and they optimise the cleaning quality compared to other materials (Poteko, Schrade, Steiner, & Zähner, 2015). With regard to ammonia emissions, a solid floor with a slope and a dung removal system is a preferable system (Braam, Ketelaars et al., 1997; Braam, Smits et al., 1997; Swierstra et al., 1995; Zhang et al., 2005), because the slope enables a rapid urine drainage from the floor surface (Schrade et al., 2013; Steiner, Keck, Keller, & Weber, 2012). In contrast, dry soiling on the floor surface has a negative effect on cleaning quality, especially in warmer seasons because the crusts formed in the absence of liquids are difficult to remove (Zähner, Poteko, Zeyer, & Schrade, 2017).

Frequent dung removal on solid floor surfaces improves housing and cow hygiene (DeVries, Aarnoudse, Barkema, Leslie, & von Keyserlingk, 2012) and leads to reduced ammonia formation and release (Braam, Ketelaars et al., 1997). The dung removal frequency strongly differs in practice (Läpke, Pelzer, & Büscher, 2010; Strahm, 2013); for example, a survey on German farms showed dung removal frequencies from one to 48 times per day (Läpke et al., 2010). Frequencies of three, six, 12 and 24 dung removal events per day were investigated in a context of cow and housing hygiene in Canada (DeVries et al., 2012). The effect of dung removal frequency on ammonia emissions was investigated in a Dutch study in the 1990s, where a dung removal frequency of 12 times per day was compared with 96 times per day (Braam, Ketelaars et al., 1997), and in a German study with dung removal performed four, 10 and 20 times per day (Schiefler, Büscher, & Schmithausen, 2013).

Finally, seasonal climatic conditions may influence the dung removal efficiency. For example, the cleaning quality may decrease in warmer seasons. Particularly warm, windy and dry conditions facilitate the drying process of soiling on the floors and thus lead to smear layers and reduced cleaning quality (Hesterberg, 2007; Steiner, 2007).

The cleaning quality achieved by dung removal systems has rarely been investigated (Schrade et al., 2013). A systematic evaluation of factors that could affect cleaning quality would be helpful to compare and further improve dung removal systems. A suitable indicator of the cleaning quality is the residual soiling mass. It refers to the soiling remaining on the floor surface after dung removal (Hesterberg, 2007; Poteko, Schrade, Steiner, & Zähner, 2014).

In previous studies, researchers used various parameters for determining the amount of soiling or residual soiling (Table 1). For example, some used a visual evaluation scheme to estimate the type and proportion of soiled areas before dung removal on solid floors of exercise areas in cattle housing (Korth, 2008; Schrade et al., 2010). Others used a ruler to measure the height of soiling piles in defined areas on solid floors in dairy housings and exercise areas (Korth, 2008) or compared these metrics on solid and perforated floors in dairy cubicle housings (Næss, Ruud, & Bøe, 2014). However, estimating the extent of soiling before dung removal is not suitable for evaluating the cleaning quality of different dung

Table 1 – Overview of methods for determining the amount of soiling or residual soiling on floor surfaces in dairy housing systems revised after Poteko et al. (2015).

Method	Estimated parameter	Advantages and disadvantages	Scale of usage	Reference
Visual estimation	Proportion, type and height of soiling	+ Simple usage (visual, with a ruler) – Visual estimation, inexact	Practical scale	Korth (2008); Schrade et al. (2010)
Measurement with a ruler	Height of soiling	+ Simple usage (with a ruler) – Measurement only on spots	Practical scale	Næss et al. (2014)
3-D-surface measurement	Void volume on the floor	+ Exact estimation – Only void volume determined	Practical & pilot-plant scale	Steiner, Keck, and Weber, (2010), Steiner, Kilian, Haidn, and Keck (2010)
Determination with a filter-paper	Moisture on the floor	+ Simple realisation – Straw mass unconsidered	Practical scale	Meyer (1985), as cited in Benz (2002)
Collecting with a scoop	Mass of soiling	+ Simple realisation (with a scoop) – Inexact on rough surface texture – Limited experimental surface	Practical scale	Pfadler (1981), as cited in Benz (2002)
Collecting with a water vacuum cleaner	Mass of soiling	– Clogging of the vacuum cleaner tube with straw	Practical scale	Haufe (2006), as cited in Korth (2008)
Collection in removal channel	Mass of removed soiling	+ Practical usage – Soiling remaining in U-shaped rail	Practical scale	Sagkob et al. (2011)
Collecting with a scoop	Mass of soiling and residual soiling	+ Simple usage (with a scoop) – Inexact on rough surface texture	Pilot-plant scale	Läpke et al. (2010)
Calculated difference between total and removed mass	Mass of removed and residual soiling	+ Suitable for various floor surfaces – Limited experimental surface	Pilot-plant scale	Hesterberg (2007)

removal systems. Steiner, Kilian, Haidn, and Keck (2010) recorded 3-D-surface measurements of void volume and topographical depth with regard to the build-up of residual soiling mass but concluded that the void volume cannot be equated with the residual soiling mass in practice.

Further methods are based on various principles to collect and to determine the extent of soiling before and after dung removal. Pfadler (1981, as cited in Benz, 2002) estimated the soiling on perforated floors in dairy housing by collecting soiling with a scoop. Läpke et al. (2010) also used a scoop to quantify the residual soiling mass after dung removal on a defined soiled solid floor in a pilot-plant scale study. This method has limitations because of soiling remaining in the rough surface texture of the floor. Likewise, the filter-paper method used by Meyer (1985, as cited in Benz, 2002) does only determine the moisture level instead of the entire residual soiling mass. Sagkob, Niedermeier, and Bernhardt (2011) used a manure scraper and assessed the collection efficiency and the removed soiling mass in a dairy housing. They found that the collection was insufficient because of the soiling remaining in the U-shaped rail, and the removed soiling mass was not an appropriate indicator to estimate the cleaning quality. Hesterberg (2007) determined the residual soiling mass on various floor surfaces by calculating the difference between a defined mass of applied soiling on the floor and the removed soiling mass. This method is limited to pilot-plant scale experiments because of the defined application of soiling. Haufe (2006, as cited in Korth, 2008) tried to collect soiling mass from a solid floor in commercial Swiss dairy loose housings by using a vacuum cleaner. This method did not work because the vacuum cleaner tube got clogged with straw.

These existing methods are inadequate for determining the residual soiling mass on a practical scale e.g. in dairy housings. Therefore, a more exact method is required to quantify the residual soiling mass and to compare the cleaning quality of different dung removal systems.

In a previous study, Poteko et al. (2014) developed step-by-step a method to quantify residual soiling manure mass on solid floor surfaces. The method was based on collecting the residual soiling manure inside a frame standing on the solid floor by using a water vacuum cleaner and weighing the collected material. Initial comparative trials on pilot-plant scale were effective in evaluating various types of floor surfaces and scraping tools. However, systematic experiments on a practical scale under Swiss dairy housing conditions are missing.

The aims of this study were to implement the described method (Poteko et al., 2014) for quantifying residual soiling mass after dung removal on a practical scale and to compare different dung removal systems with regard to their cleaning quality.

The measurement concept consists of two experiments to enable a step-by-step investigation of factors influencing the cleaning quality. In experiment 1 the residual soiling masses after dung removal with two scraping tools (hard rubber lip and metal blade) combined with two rubber mat types (common rubber mat and soft rubber mat) were determined and compared in one season. Based on these results, in experiment 2 the most promising combination of scraping tool and rubber mat was used, to quantify the residual soiling masses on two floor types (with and without transversal slope of 3%) combined with two dung removal frequencies (three and 12 times per day) in three seasons (summer, transition period and winter).

2. Material and methods

2.1. Housings

The measurements were carried out at Agroscope's experimental farm at Taenikon in Switzerland in two dairy housings at the locations Taenikon and Waldegg. Both were naturally ventilated dairy loose housings with cubicles and an outdoor exercise area. The aisles inside the housings had solid floors with automatic stationary manure scrapers. In both housings, the dairy herds consisted of Brown Swiss and Swiss Fleckvieh breeds. The cows were milked twice a day and fed with a total mixed ration based on maize silage, grass silage, hay, and sugar beet pulp silage, and concentrates from automatic concentrate feeders.

2.1.1. Experimental dairy housing in Taenikon

The dairy housing was built for 62 cows and occupied by 52 lactating and dry cows (Fig. 1). The feeding aisle and cubicle access area had a transversal slope of 3% and a urine-collecting gutter in the middle. The floors were equipped with rubber mats. The available exercise area was 9.62 m^2 per cow. The scraping tool of the automatic manure scraper with urine-collecting gutter cleaner (Breitschieber Mobile, Krieger, Ruswil, Switzerland) is exchangeable. The speed was approximately 4 m min^{-1}. During the experimental period, the cows had access to the outdoor exercise area.

2.1.2. Experimental dairy housing for emission measurements in Waldegg

The dairy housing consisted of two equal experimental compartments (Fig. 2), each for 20 lactating cows. The floor type is variable. The floors of both compartments (7.59 m^2 per cow) were equipped with the same common rubber mats (KURA P, Gummiwerk KRAIBURG Elastik GmbH, Tittmoning, Germany). The scraping tool of the automatic manure scraper (Breitschieber Mobile, Krieger, Ruswil, Switzerland) was a hard rubber lip. The speed was approximately 4 m min^{-1}. The facades along the feeding table and along the outdoor exercise area were conducted as flexible curtains. During the several measurement periods the position of the curtains was not changed. In summer, the curtains on the longitudinal sides were completely open; in the transition period the curtains along the feeding table were closed and those along the outdoor exercise area were open; and in winter, the curtains on all sides were closed.

2.2. Experimental design

The residual soiling mass was quantified and effects on residual soiling mass were compared systematically in two separate experiments. In experiment 1, two scraping tools and two rubber mat types were compared in the experimental dairy housing in Taenikon (see 2.1.1) in winter 2015. In

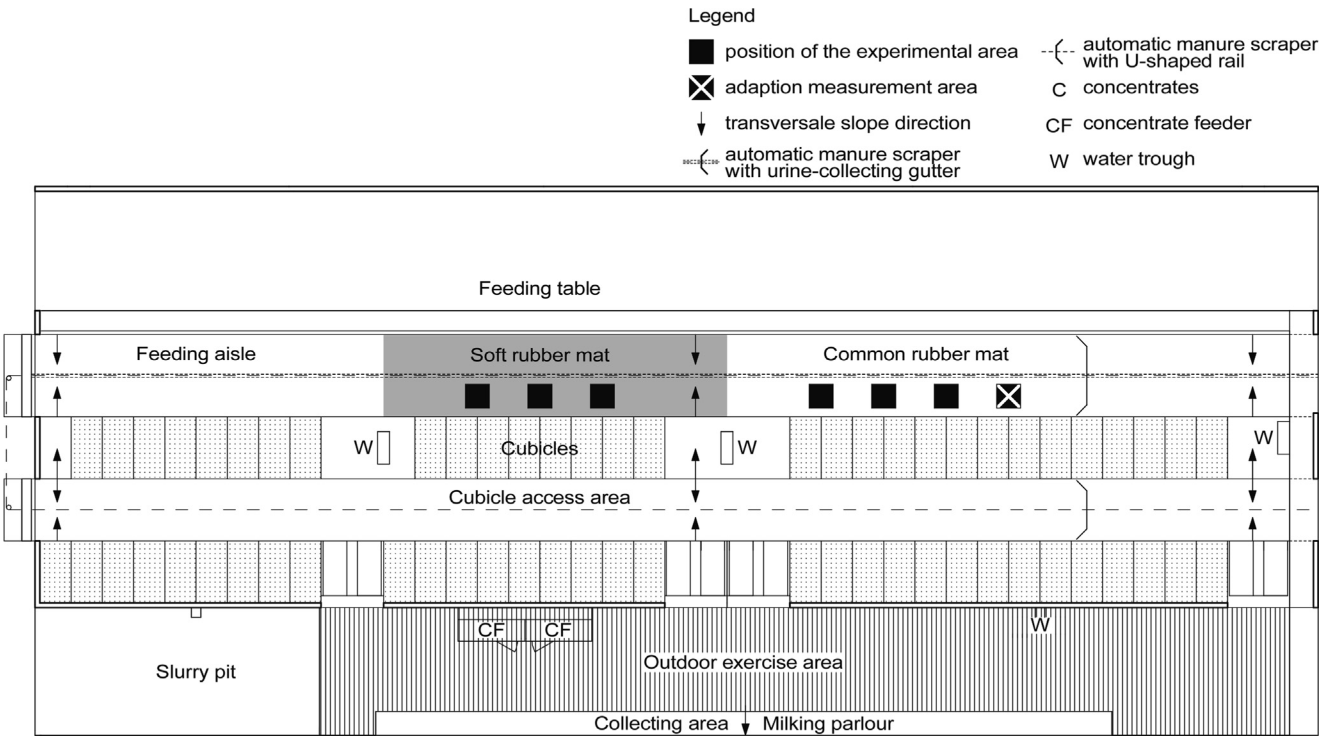

Fig. 1 – Schematic diagram showing the layout of the experimental dairy housing in Taenikon with different rubber mat types and with positions of the experimental areas of 1 m^2 each (black squares) and the adaption measurement area (black square with white cross).

experiment 2 12 variants consisted of two floor types, two dung removal frequencies and three seasons. These investigations were carried out in the experimental dairy housing for emission measurements in Waldegg (see 2.1.2) in summer, autumn and winter 2015.

2.2.1. *Experiment 1: comparison of scraping tools and rubber mat types*

The aim of experiment 1 conducted in the experimental dairy housing in Taenikon (see 2.1.1) was the comparison of the residual soiling mass when using a metal blade or a hard rubber lip as scraping tools, each combined with a common rubber mat and a soft rubber mat. The common rubber mat (KURA P) and the soft rubber mat (prototyp) were manufactured by Gummiwerk KRAIBURG Elastik GmbH, Tittmoning in Germany. The prototype was made specially for investigations in Taenikon and consists of the same upper side like the floor rubber mat, KURA P′ and of a bottom side like the cubicle rubber mat,CALMA′, whereas nubs on the bottom side enabled claws to sink deeper than on the common rubber mat. Measurement areas were positioned in the feeding aisle. To minimise evaporation of water from residual soiling during the measurements, the experiment was carried out in winter. In total four variants were investigated. Six repetitions were carried out per variant, three repetition each on two consecutive days. The dung removal frequency was six times per day. The dung removal events (4:00 a.m., 7:00 a.m., 9:00 a.m., 1:00 p.m., 4:00 p.m. and 6:00 p.m.) were adjusted to management activities like milking and feeding as well as to the diurnal pattern of the herd. During the measurements, the manure scraper was stopped after reaching each measurement position, to clean the respective measurement position just before vacuuming (see 2.3).

2.2.2. *Experiment 2: comparison of floor type, dung removal frequency and season*

In the experimental dairy housing for emission measurement Waldegg (see 2.1.2), the residual soiling mass on two floor types without and with transversal slope (3%) combined with different dung removal frequencies (three and 12 times per day) was quantified in three seasons (summer, transition period and winter). In all variants, floors were equipped with the common rubber mat, and a hard rubber lip was used as scraping tool. The experiment was conducted in the feeding aisle and lasted four days per season. Per day two variants each with three repetitions were performed. Analogous to Experiment 1 six repetitions per variant were carried out. The dung removal at a frequency of 12 times per day was performed approximately every 2 h. The dung removal events of three times per day were carried out at 5:30 a.m., 11:15 a.m. and 7:00 p.m. adjusted to activities such as milking and feeding. Analogous to experiment 1, the manure scraper was moved step-by-step to clean the respective measurement position just before vacuuming (see 2.3).

2.3. *Measuring method*

We implemented, on a practical scale, the method to quantify residual soiling mass on solid floors that had been developed

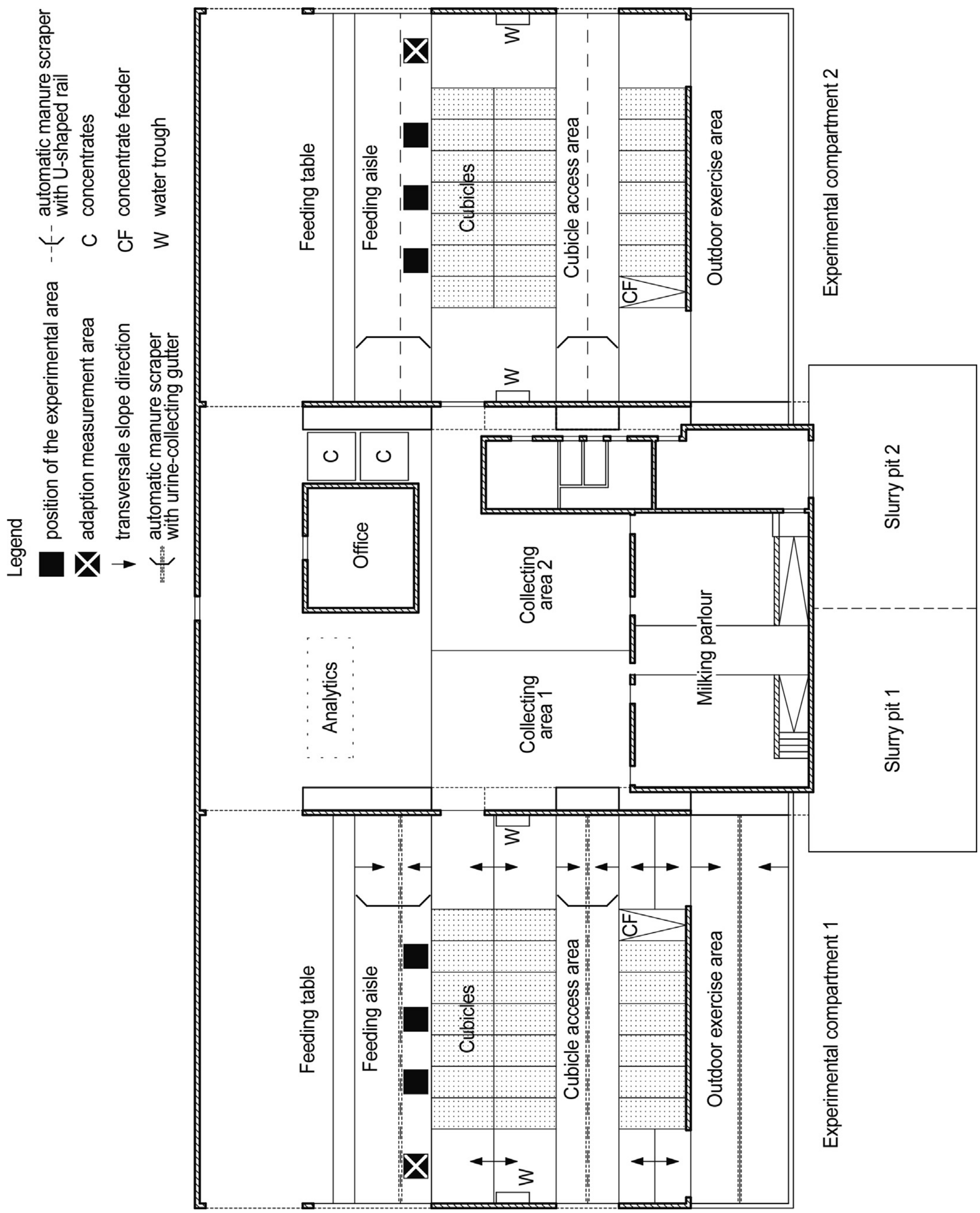

Fig. 2 – Schematic diagram showing the layout of the experimental dairy housing for emission measurements in Waldegg with different floor types and with positions of the experimental areas of 1 m^2 each (black squares) and the adaption measurement area (black square with white cross).

and evaluated on pilot-plant scale by Poteko et al. (2014). The experimental area was defined as 1.00 m^2 and framed with a rubber seal (Cellular rubber RG [140 kg m^{-3}] CR), which had a width of 30 mm and a height of 10 mm, and was fixed on a 1-m^2 (area inside the frame) wooden frame. A weight (300 kg) on the frame generated a pressure of 2.6 N cm^{-2} on the rubber seal and thus ensured a waterproof border between the experimental area inside the frame and the ambient floor surface (Fig. 3).

The residual soiling inside the frame was diluted with 1 L of water (0–10 °C) for a complete collection of residual soiling by using a water vacuum cleaner equipped with a crevice tool (WD 2.400 M, Kärcher, Winnenden, Germany). The cold water minimised the evaporation from the residual soiling during vacuuming. The limited vacuuming duration of exactly 7 min ensured constant evaporation in the water vacuum cleaner and enabled the complete collection of residual soiling inside the frame. After each collection of residual soiling, the entire

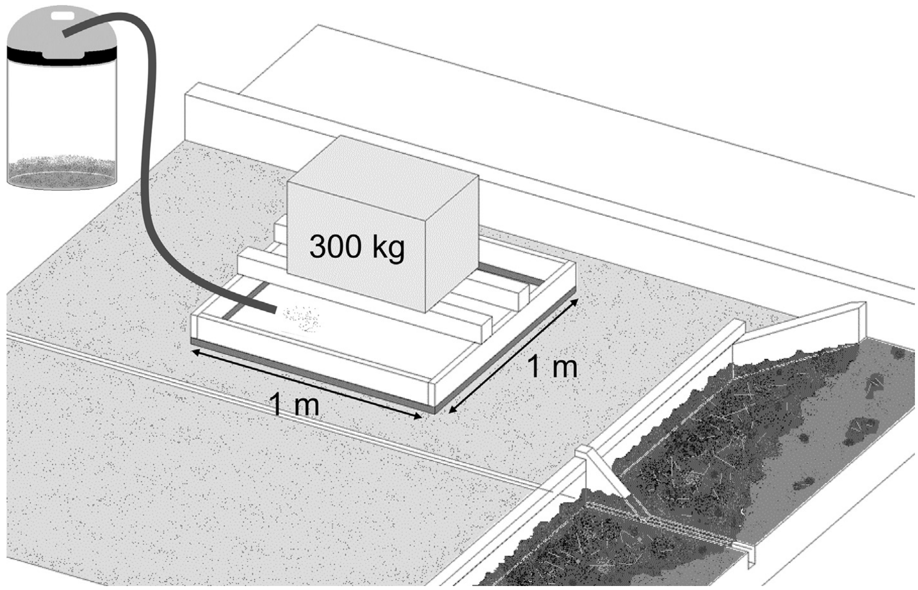

Fig. 3 – Scheme of the measuring method: the frame limiting the experimental area (1 m²) on the solid floor with a waterproof border for collecting the residual soiling mass with a water vacuum cleaner after dung removal.

water vacuum cleaner with the collected residual soiling inside was weighed with a balance (SG16001, Mettler Toledo, Switzerland). The residual soiling mass [g m^{-2}] was determined by calculating the weight difference between the full and the empty vacuum cleaner with the water used for dilution.

The measurements were carried out between 9:00 a.m. and 12:00 p.m. Each variant was investigated on two individual days at a total of six positions (each day three measurements for one variant). Each measurement position per variant and day means a repetition. The positions were equally distributed over a predefined experimental area in the feeding aisles between the cubicles and the U-shaped rail to get a representative sample (Figs. 1 and 2). Based on experiences of preliminary tests (Poteko, 2014), an initial adaption measurement (position marked in Figs. 1 and 2 as black squares with white cross) was made to precondition the measuring equipment each measurement day, to practise the measurement procedure and to ensure the standard conditions for all subsequent measurements. During the measurements, the cows had no access to the investigated feeding aisle for about 1 h.

To describe the measurement situation and to identify variables influencing the residual soiling mass, the following accompanying parameters were recorded: air temperature, floor temperature, floor slope, dry-matter content of soiling and dry-matter content of residual soiling. The air temperature (Testo 175 H1, Testo, Lenzkirch, Germany) was measured each day at the beginning and the end of measurements (Taenikon: in the middle of six positions of the experimental area; Waldegg: in the middle of three positions of the experimental area, each compartment separately). The measurement of the floor temperature (Fluke 51 K/J Thermometer, Fluke Corporation, Everett WA, USA) for each measurement was performed during the vacuuming process next to the experimental area outside of the frame (floor inside the frame was cooled by water). The gradient of the floor was recorded for each measurement position. One composite sample of soiling was taken per measurement day in front of the manure scraper for determination of the dry-matter content. The residual soiling in the water vacuum cleaner of each measurement was used to determine the dry-matter content. The dry-matter content was determined in the laboratory with drying at 105 °C up to a constant mass.

2.4. *Statistical analysis*

Datasets were analysed using generalised least squares models with TIBCO Spotfire S+® software version 8.2 for Windows. The distributional properties of data from experiments 1 and 2 were visually checked using a normal quantile–quantile plot of the residuals. Datasets of both experiments were normally distributed. The significance threshold was set at 0.05 using a confidence interval of 95%. The models were built stepwise based on accompanying parameters (air temperature, floor temperature, dry-matter content of soiling; dry-matter content of residual soiling), whereby the non-significant parameters were eliminated. For experiment 1, the model was composed of residual soiling mass as the response variable, and the fixed effects rubber mat type and scraping tool and their interaction. For experiment 2, the model was composed of residual soiling mass as the response variable, and the fixed effects dung removal frequency, floor type and season and their interactions. Additionally, the effects of dung removal frequency and floor type were tested for each individual season. For this purpose, three separate models for summer, transition period and winter were composed of residual soiling mass as the response variable, and the fixed effects dung removal frequency and floor type and their interactions.

3. Results

3.1. Experiment 1: comparison of scraping tools and rubber mat types

Climatic conditions inside the housing were nearly the same during the experiment. The air temperatures ranged between −0.4 °C and 3 °C and represented typical winter conditions (Table 2). The dry-matter content of soiling from the feeding aisle did not differ between variants (12–13%), whereas dry-matter content of residual soiling was with 16% higher in variant ‘common rubber mat combined with hard rubber lip’ than in all other variants with 12% (Table 2). The mean values of residual soiling mass after dung removal in all variants ranged between 174 g m^{-2} in variant common rubber mat with hard rubber lip and 243 g m^{-2} in variant soft rubber mat with metal blade (Fig. 4). Dung removal with the hard rubber lip left a smaller ($p = 0.001$) residual soiling mass compared with the metal blade on both investigated rubber mats. The residual soiling mass was smaller ($p = 0.001$) on the common than on the soft rubber mat regardless of scraping tool. Furthermore, we found a significant interaction between rubber mat type and scraping tool ($p = 0.029$).

3.2. Experiment 2: comparison of floor types, dung removal frequencies and seasons

Climatic conditions showed typical seasonal values (Table 3). The mean residual soiling masses ranged from 162 g m^{-2} in variant floor without slope combined with 12 dung removals per day in winter to 303 g m^{-2} in variant floor with slope with 12 dung removals per day in summer (Fig. 5). The dry-matter contents of soiling and residual soiling reached maximal values in summer (Table 3). Warmer seasons showed higher residual soiling mass ($p < 0.001$). In addition, a significant effect on the residual soiling mass of the triple interaction of season, floor type and dung removal frequency ($p = 0.01$). Furthermore, the interaction of season and floor type showed a trend to influence residual soiling mass ($p = 0.059$). The standard deviations of the individual values within the variants were higher in summer and transition period than in winter (Table 3). Furthermore, the range between mean values was larger in the two warmer seasons than in winter (Fig. 5).

The additional statistical analysis of the winter dataset showed no significant effect of dung removal frequency, floor type or air temperature on the residual soiling mass. In the transition period dataset, the interaction of floor type and dung removal frequency had a significant effect on residual soiling mass ($p = 0.004$). The summer dataset showed a clear effect of the floor type. The residual soiling mass on the floor with slope was significantly larger than on the floor without slope ($p = 0.037$) at both dung removal frequencies.

4. Discussion

4.1. Measuring method

The method that Poteko (2014) and Poteko et al. (2014) developed, evaluated and used on pilot-plant scale has proven appropriate and sufficiently accurate for quantifying residual soiling mass on a practical scale We found significant differences in the collected residual soiling mass between several investigated factors (e.g. common vs. soft rubber mat; hard rubber lip vs. metal blade) in experiment 1 (see Table 2 and Fig. 4) as well as significant seasonal effects and effects of dung removal frequency and floor gradient in warmer seasons in experiment 2 (see Table 3 and Fig. 5) although no differences in cleaning quality were visually recognisable. Furthermore, our results confirm results of a comparison of scraping tools from pilot-plant scale experiments conducted by Poteko et al. (2014) (Fig. 6). One of the major strengths of the method lies in the direct quantification of the residual soiling mass by weighing the collected soiling. The mass from the hollows of the surface structure is also considered. In contrast, previous methods were based on indirect quantification of residual soiling mass. For example, in pilot-plant scale experiments, Hesterberg (2007) determined the residual soiling mass by the difference of a defined applied mass and the removed mass, a method that is not suitable for experiments on a practical scale.

Sagkob et al. (2011) collected the removed soiling of a whole aisle to evaluate the cleaning quality on a practical scale. However, their applied collection method was insufficient because part of the soiling remained in the U-shaped rail. In addition, aspects like release of excrements by the animals, animal activity and climate were not taken into account.

Table 2 – Mean values (with standard deviations in brackets) of air and floor temperature, dry-matter content (DM) of soiling before dung removal, DM of soiling and residual soiling mass for four experimental variants.

Rubber mat	Scraping tool	Air temp. [°C]	Floor temp. [°C]	DM of soiling [%]	DM of residual soiling [%]	Residua0 soiling mass 0 [g m^{-2}]	Analysis of variance
		n = 4	n = 6	n = 2	n = 6	n = 6	
Common	Hard rubber lip	−0.4 (1.8)	0.6 (1.2)	12 (*)	16 (3.1)	174 (15.2)	a
Common	Metal blade	3.0 (0.3)	2.3 (1.2)	13 (0.3)	12 (1.2)	230 (20.0)	b
Soft	Hard rubber lip	−0.4 (1.8)	0.6 (0.9)	12 (*)	12 (3.3)	230 (27.8)	b
Soft	Metal blade	3.0 (0.3)	2.3 (0.9)	13 (0.3)	12 (1.0)	243 (16.7)	c

Residual soiling mass means followed by the same letter in the column do not significantly differ ($p \leq 0.05$). DM = dry-matter content, n = number of measurements for one variant, * = not available, because only one measurement performed, temp. = temperature.

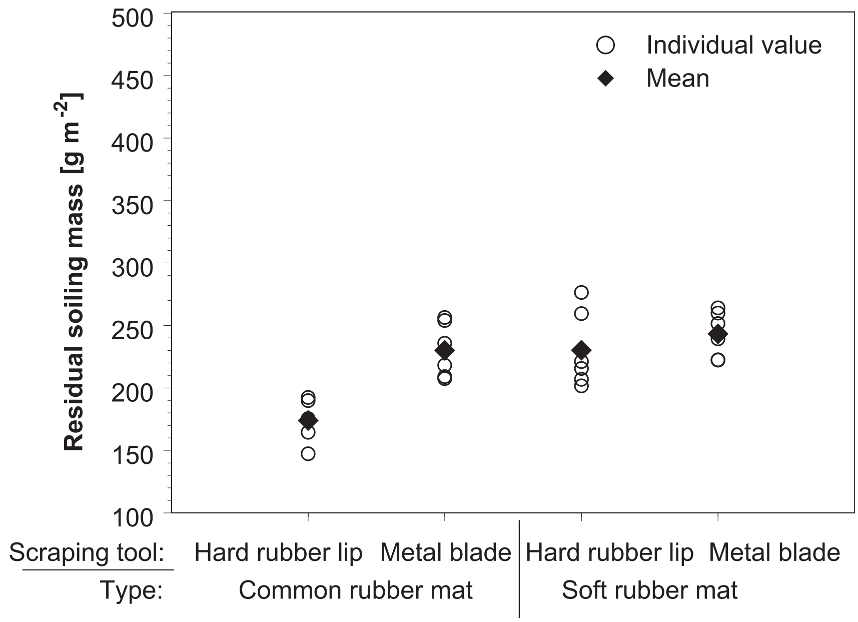

Fig. 4 – Residual soiling mass [g m^{-2}] as individual values (open circles) and mean values (filled diamonds) presented per scraping tool (hard rubber lip and metal blade), combined with rubber mat type (common rubber mat and soft rubber mat) on the floor with transversal slope of 3% with dung removal frequency of six times per day in winter.

Collecting the residual soiling by a water vacuum cleaner has advantages in comparison with other methods. Scraping off the residual soiling completely by using a scoop, as done by Läpke et al. (2010), is not possible because of the surface texture of the floor. In contrast to Haufe (2006, as cited in Korth, 2008), who used a water vacuum cleaner to collect the soiling from floors on Swiss dairy farms, we had no problems with clogging of the vacuum cleaner with straw when vacuuming the residual soiling. To optimise the suction quality, we had diluted the residual soiling with a defined mass of cold water, which improved loosening the soiling from the rubber mat surface. We implemented this optimisation by bordering the experimental area (1 m^2) using a waterproof frame with a rubber seal. Consequently, the water vacuum cleaner could collect the entire residual soiling mass from the experimental area.

The accuracy of the method was also optimised by a standardised collection procedure, which was first practised by carrying out an adaption measurement at the beginning of each experimental day. In addition, the standardised vacuuming duration and dilution with a defined mass of cold water kept evaporation during vacuuming at the same level for all collections.

Table 3 – Mean values (with standard deviations in brackets) of air and floor temperature, dry-matter content (DM) of soiling before dung removal, DM of soiling and residual soiling mass for 12 experimental variants.

Season	Dung removal frequency [times per day]	Gradient of slope [%]	Air temp. [°C]	Floor temp. [°C]	DM of soiling [%]	DM of residual soiling [%]	Residual soiling mass [g m^{-2}]	Analysis of variance			
			n = 4	n = 6	n = 2	n = 6	n = 6	I	II		
									W	T	S
Winter	3	0	4.0 (0.6)	5.7 (0.9)	13 (0.2)	13 (0.7)	182 (25.5)	a	a		
	3	3	3.4 (0.5)	4.7 (0.4)	14 (0.5)	15 (1.1)	168 (29.4)		a		
	12	0	2.7 (0.8)	3.6 (0.6)	13 (0.2)	16 (2.9)	162 (27.9)		a		
	12	3	1.4 (1.1)	3.3 (0.6)	12 (0.4)	14 (1.4)	193 (41.6)		a		
Transition	3	0	15.8 (1.5)	15.4 (1.1)	13 (0.6)	16 (3.4)	183 (38.7)	b		a	
period	3	3	15.4 (1.8)	14.5 (0.5)	12 (0.6)	17 (4.6)	248 (82.7)			b	
	12	0	12.5 (0.5)	12.4 (2.0)	12 (0.1)	11 (0.6)	259 (36.8)			b	
	12	3	11.8 (0.8)	11.1 (0.5)	10 (3.7)	14 (1.0)	175 (22.7)			a	
Summer	3	0	22.0 (4.1)	20.6 (1.9)	10 (3.0)	16 (5.3)	218 (54.0)	c			a
	3	3	21.8 (4.0)	21.2 (2.9)	11 (2.4)	16 (5.3)	280 (80.8)				b
	12	0	25.2 (2.1)	23.2 (0.9)	14 (0.3)	22 (3.6)	234 (24.2)				a
	12	3	24.8 (1.9)	22.2 (0.5)	17 (2.1)	22 (3.6)	303 (84.9)				b

Residual soiling mass means followed by the same letter in the column do not significantly differ ($p \leq 0.05$). I = analysis included all three seasons, II = analysis of residual soiling mass of each individual season (W = winter, T = transition period, S = summer), DM = dry-matter content, n = number of measurements for one variant, temp. = temperature.

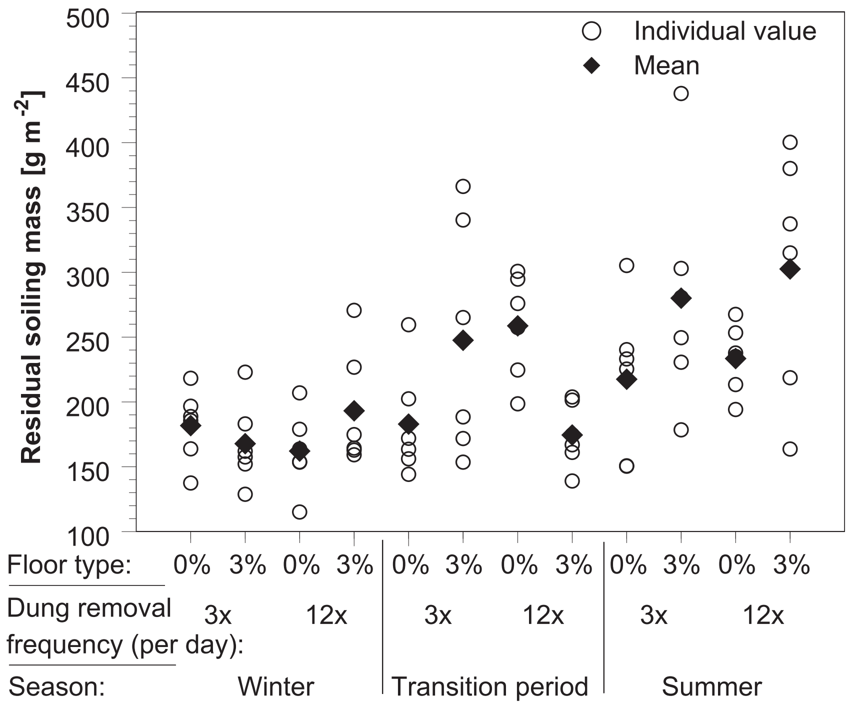

Fig. 5 – Residual soiling mass [g m^{-2}] as individual values (open circles) and mean values (filled diamonds) differentiated according to season (summer, transition period, winter), dung removal frequency (three and 12 times per day) and floor type (without slope and transversal slope of 3%) after dung removal with a hard rubber lip as scraping tool on a common rubber mat.

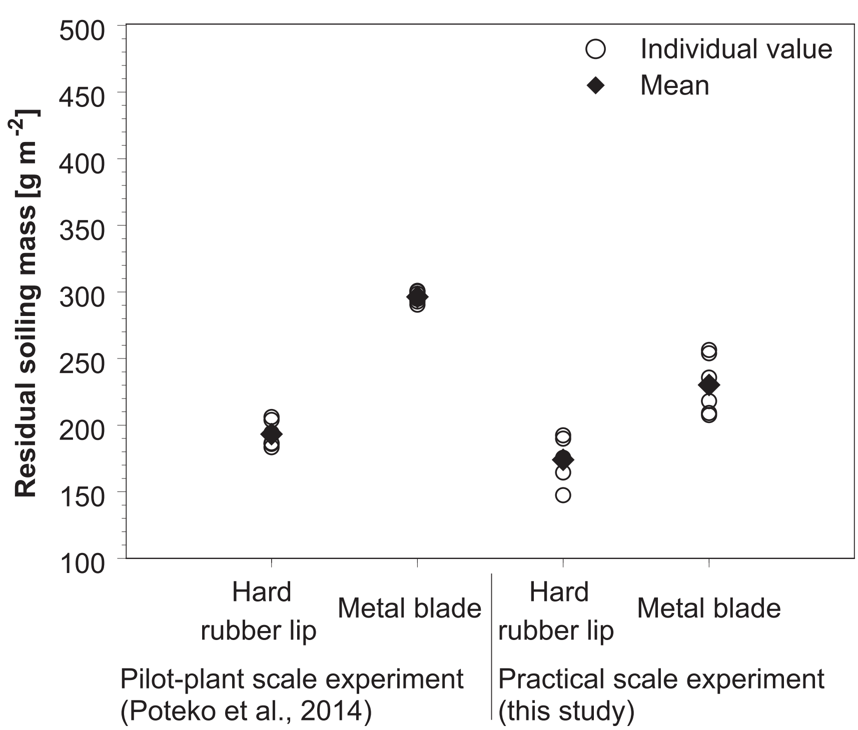

Fig. 6 – Residual soiling mass [g m^{-2}] as individual values (open circles) and mean values (filled diamonds) differentiated according to scraping tool (hard rubber lip and metal blade) combined with a common rubber mat in a previous pilot-plant scale experiment (floor without slope in summer) and the present practical scale experiment (floor with slope in winter).

Our measurement concept consisting of two experiments enabled the stepwise investigation of various factors with potential influence on cleaning quality. Based on the results of experiment 1, the most compatible combination of scraping tool and rubber mat was used in experiment 2, where floors without and with slope, low and high dung removal frequencies and seasons were varied.

4.2. *Scraping tool*

The significant effect of the scraping tool on residual soiling mass found in experiment 1 confirmed the results of pilot-plant scale experiments (Fig. 6) using the same measuring method (Poteko et al., 2014). Poteko et al. (2014) compared various scraping tools (metal blade, hard rubber lip, soft rubber lip, brush, combination of hard rubber lip and brush) on two floor surface types (concrete floor, common rubber mat). The most efficient scraping tools on both floor types were the rubber lip and brush variants. As found in the pilot-plant study, the residual soiling mass in the present study was smaller when using the hard rubber lip than the metal blade to remove manure from the common, as well as the soft, rubber mat. In contrast to the present study, in which the extent of soiling was inhomogeneous, the experimental areas in the pilot-plant study had a standardised amount of soiling and were not exposed to further influences (e.g. animal activity, dynamic climatic conditions in the naturally ventilated housing). Nonetheless, the averages of residual soiling masses after dung removal with the hard rubber lip (193 g m^{-2}) and the metal blade (296 g m^{-2}) on the common rubber mat were slightly larger in the pilot-plant experiment than in the same variants of the present study (174 g m^{-2} and 230 g m^{-2}, respectively) (Fig. 6). The flexible and elastic lip was able to adjust to the roughness and small bumps on the surface and thus improve the cleaning quality on different floor surface types.

Although the quantified residual soiling masses on 1 m^2 seem to be very small, the total floor surfaces in dairy housings are much larger, stressing the importance of efficient dung removal. For example, the feeding aisle in the experimental dairy housing in Taenikon comprises around 180 m^2. The extrapolation based on experiment 1 showed that the residual soiling mass on the common rubber mat after dung removal with hard rubber lip (31 kg per 180 m^2) would increase by 10 kg on the same rubber mat after usage of the metal blade.

According to Snoek et al. (2017), dung removal quality in commercial dairy housings can often visually be recognised as not satisfying because of aspects such as wear and tear of scraping tools. Companies recommend the use of flexible rubber lips as scraping tools on rubber mats. Our results confirm the importance of the adjustment of scraping tool and floor surface for cleaning quality (Poteko et al., 2014).

4.3. *Rubber mat type*

The residual soiling mass on the soft rubber mat was significantly larger than on the common rubber mat, although the surface texture was the same on both rubber mats. According to Kilian (2007), the void volume of the surface influences the extent of residual soiling mass. Hesterberg (2007) found larger residual soiling masses on floor surfaces with larger void volume in pilot-plant experiments. Poteko et al. (2014) investigated a rubber mat and a concrete floor in pilot-plant scale experiments using the same measuring method as used in experiments 1 and 2. Mean values of the residual soiling mass on the common rubber mat with 167 g m^{-2} to 296 g m^{-2} were evidently smaller than on the concrete floor with 472 g m^{-2} to 634 g m^{-2} after dung removal using five different scraping tools (Poteko et al., 2014). Considering the void volume, the concrete floor with larger void volume than the tested rubber mat enabled an accumulation of a larger residual soiling mass after dung removal (Steiner, Keck, & Weber, 2010; Steiner, Kilian, Haidn, & Keck 2010). In our study, despite the same rubber surface texture, the softness of the rubber mat seemed to diminish the adjustment of the rubber mat and the scraping tool and hence the cleaning quality.

4.4. *Floor type*

The clear effect of floor type in summer with around 30% larger residual soiling mass on the floor with slope than that without slope can be explained by dried soiling causing a lower cleaning quality. A slope of 3% enables a rapid drainage of the urine from the floor surface (Steiner, Keck, & Weber, 2010). A visual estimation of soiling type on floors showed less urine and wet faeces on the floor surface with than one without slope under the same climatic conditions (Zähner et al., 2017). Additionally, the warm summer temperatures facilitate the drying process (Hesterberg, 2007). Therefore, to reduce the formation of smear layers on warm days, water spraying before dung removal might improve the cleaning quality (Steiner, 2007). Systematic experiments in pilot-plant scale show a positive effect on the cleaning quality by water spraying on a soiled experimental area with a defined smear layer (Poteko, 2014).

4.5. *Dung removal frequency*

A significant effect of the dung removal frequency in experiment 2 (three or 12 times per day) on residual manure mass was only found in the interaction with floor type and season. However, overall, the dung removal frequency had no meaningful influence on residual soiling mass. The significant interaction of the dung removal frequency with floor type in the transition period can hardly be explained. In this case, the results showed an increase in residual soiling mass when the dung removal frequency was changed from three to 12 times per day on the floor without slope but a decrease on the floor with slope. This unexpected result could be a consequence of other effects (e.g. slightly differentiated dry-matter content of soiling before dung removal).

The comparison of three dung removal frequencies (three, six and 12 times per day) from combined data of experiments 1 and 2 (Fig. 7) under identical conditions concerning scraping tool, rubber mat type, floor type and season indicated an increase in residual soiling mass along with raised dung removal frequency. Nevertheless, because the mean values of the residual soiling masses were very close to each other and

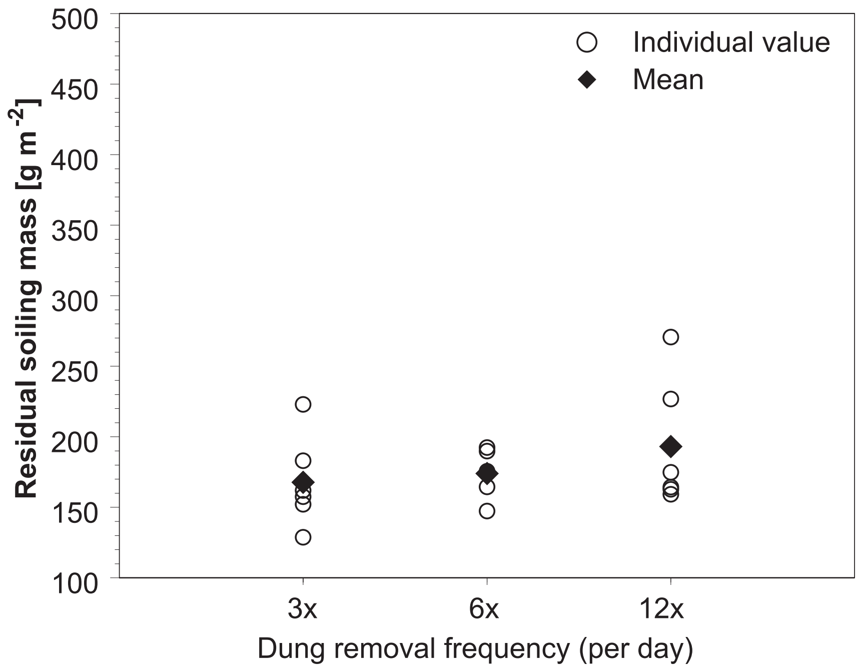

Fig. 7 – Residual soiling mass [g m^{-2}] as individual values (open circles) and mean values (filled diamonds) differentiated according to dung removal frequency (three, six and 12 times per day) on a floor with transversal slope of 3% after dung removal with a hard rubber lip on a common rubber mat in winter.

Table 4 – Comparison of mean values (with standard deviations in brackets) of air and floor temperature, dry-matter content (DM) of soiling before dung removal, DM of residual soiling and residual soiling mass for three dung removal frequencies on a common rubber mat on a floor with slope (3%) and use of a hard rubber lip in winter.

Dung removal frequency [times per day]	Air temperature [°C]	Floor temperature [°C]	DM of soiling [%]	DM of residual soiling [%]	Residual soiling mass [g m^{-2}]
	n = 4	n = 6	n = 2	n = 6	n = 6
3	3.4 (0.5)	4.7 (0.4)	14 (0.5)	15 (1.1)	168 (29.4)
6	−0.4 (1.8)	0.6 (1.2)	12 (0)	16 (3.1)	174 (15.2)
12	1.4 (1.1)	3.3 (0.6)	12 (0.4)	14 (1.4)	193 (41.6)

DM = dry-matter content, n = number of measurements for one variant.

the standard deviations were small, this trend may be negligible (Table 4).

Although the soiling accumulation on the floor between two dung removals lasted few or even several hours the residual soiling mass indicates the start level. Hence, the cleaning quality is relevant for areas' soiling beside dung removal frequency.

4.6. *Season*

In experiment 2, the season had a significant effect on residual soiling mass. Warm and windy conditions seemed to lead to larger residual soiling mass. Especially in summer, when the curtains on the longitudinal sides of the naturally ventilated dairy housing in Waldegg were open, the air flow through the housing may, in addition to the warm temperatures, facilitate the drying of the soiling. According to Hesterberg (2007), dried soiling led to smear layers and increased the residual soiling mass, and thus decreased the cleaning quality. Another indication of inconsistent cleaning quality in our study was the higher standard deviation of residual soiling mass when climatic conditions were warmer (Table 3).

The significant interaction of season, dung removal frequency and floor type shows the complexity of dung removal. The aim of an optimised dung removal system is to ensure a good cleaning quality independent of the season. In practise, water spraying before dung removal is suggested to increase the cleaning quality in hot climatic conditions (Steiner, 2007). A positive effect on cleaning quality was found in pilot-plant scale experiments when water was sprayed on a soiled experimental area with a defined smear layer compared to a variant without water spraying (Poteko, 2014). In further research, the effect of spraying on cleaning quality should be investigated on a practical scale.

5. Conclusions

The method to quantify residual soiling mass on solid floor surfaces by vacuuming soiling from a framed experimental area has proven useful on a practical scale. With this method and the measuring concept consisting of two systematic experiments, we were able to identify factors with significant effects on the residual soiling mass, and thus derive recommendations for practical application and need for further research.

The scraping tool and the rubber mat type had a significant effect on residual soiling mass. Compared with the metal blade, the more flexible rubber lip used as scraping tool improved the cleaning quality. These results confirmed the importance of the adjustment between scraping tool and floor surface for good cleaning quality. Out of the tested variants, the combination of the common rubber mat and the rubber lip as scraping tool proved to be recommended with regard to cleaning quality.

Several significant interactions of factors affecting residual soiling mass emphasised the complexity of dung removal. In particular, different climatic conditions may cause different effects on other factors.

The significant seasonal effect in experiment 2 with increased residual soiling mass in summer was enhanced by the effect of a floor with 3% slope. Warm, windy conditions and the absence of liquids (e.g. on sloped floors) led to accelerated drying soiling. Targeted sprinkling of water may improve cleaning quality in these situations. The effect of water sprinkling on the residual soiling mass, as well as on smear layer formation and ammonia-emission, should be quantified in further investigations on a practical scale.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.biosystemseng.2018.04.006.

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