

AperTO - Archivio Istituzionale Open Access dell'Università di Torino

**Assessing particulate matter (PM10) emissions from outdoor runs in laying hen houses by integrating wind tunnel and lab-scale measurements**

**This is the author's manuscript**

*Original Citation:*

*Availability:*

This version is available <http://hdl.handle.net/2318/1799201> since 2021-09-02T11:51:36Z

*Published version:*

DOI:10.1016/j.biosystemseng.2021.07.017

*Terms of use:*

Open Access

Anyone can freely access the full text of works made available as "Open Access". Works made available under a Creative Commons license can be used according to the terms and conditions of said license. Use of all other works requires consent of the right holder (author or publisher) if not exempted from copyright protection by the applicable law.

(Article begins on next page)

1 **Assessing particulate matter (PM<sub>10</sub>) emissions from outdoor runs in laying hen**  
2 **houses by integrating wind tunnel and lab-scale measurements**

3 Jacopo Maffia<sup>ab\*</sup>, André J.A. Aarnink<sup>b</sup>, Johan Ploegaert<sup>b</sup>, Elio Dinuccio<sup>a</sup>, Paolo  
4 Balsari<sup>a</sup>, Hilko Ellen<sup>b</sup>

5 <sup>a</sup> Dipartimento di Scienze Agrarie, Forestali e Alimentari, Università di Torino, Largo  
6 Paolo Braccini 2, 10095 Grugliasco, Italy

7 <sup>b</sup> Wageningen University and Research, Livestock Research, P.O. Box 338, 6700 AH  
8 Wageningen, the Netherlands

9  
10 \*corresponding author

11 *email:* jacopo.maffia@unito.it; *present address:* Largo Paolo Braccini 2, 10095  
12 Grugliasco, Italy

13  
14 **Abstract**

15 Laying hen houses are a known source of fine particulate matter (PM), but no  
16 information is available on the contribution of outdoor runs to the overall emissions.  
17 This study aims to investigate some of the main factors driving PM emissions from  
18 outdoor runs. A wind tunnel device was built to assess the effect of hen density (HD,  
19 hens m<sup>-2</sup>) on PM emissions from outdoor runs. Moreover, a laboratory trial, using a soil  
20 resuspension chamber, was conducted to describe the influence of soil moisture on  
21 the emissions. The gathered information was then used to estimate PM<sub>10</sub> emissions  
22 over a 1-year period. PM emissions increased exponentially with increasing HD and  
23 decreased exponentially with increasing soil water content. The average PM<sub>10</sub>  
24 emissions from hen activities at the study farm, estimated using meteorological data  
25 from year 2019, were of 8.9 mg hen<sup>-1</sup> d<sup>-1</sup>. This emission is much lower than those  
26 reported by previous studies for indoor hens rearing.

27 **KEYWORDS:** particulate matter; emissions; laying hens; area source; wind tunnel

## 29 HIGHLIGHTS

- 30 • A new method to assess PM emissions from outdoor runs in hen houses was  
31 developed;
- 32 • PM<sub>10</sub> emissions for hen activity in outdoor runs were estimated;
- 33 • An exponential increase of PM<sub>10</sub> emission was observed with increasing hen  
34 density;
- 35 • The effect of soil moisture on soil derived PM<sub>10</sub> emission was assessed.  
36

37

### 38 **1. Introduction**

39 High environmental concentrations of particulate matter (PM) are regarded as a cause  
40 of concern for human health (Pope, 2007). Livestock activities are long known to play  
41 an important role in PM concentration raises both in indoor and outdoor environments  
42 (Cambra-López, Aarnink, Zhao, Calvet, & Torres, 2010; EEA, 2016). In fact, both the  
43 coarser (PM<sub>10</sub>; particles with an aerodynamic diameter <10 µm) and finer (PM<sub>2.5</sub>;  
44 particles with an aerodynamic diameter <2.5 µm) fractions of PM are held responsible  
45 for negative health effects in farmers and local residents surrounding livestock houses.  
46 Furthermore, high dust concentrations affect indoor air quality and health and welfare  
47 of animals (Borlée et al., 2017; María Cambra-López et al., 2010). Several studies  
48 have addressed the issue of PM emissions from poultry houses, quantifying the  
49 emission fluxes (Hayes, Curran, & Dodd, 2006; Roumeliotis & Van Heyst, 2008; Yao  
50 et al., 2018) and proposing mitigation measures (M. Cambra-López, Winkel, Harn,  
51 Ogink, & Aarnink, 2009; R. W. Melse, P. Hofschreuder, & N. W. M. Ogink, 2012; Winkel  
52 et al., 2016). Most of these studies focused on emissions coming from poultry houses,  
53 while very little information is available on the contribution of the outdoor runs on the  
54 overall emissions. This is partially due to the fact that assessing emissions from area  
55 sources in open space environments presents some difficulties, especially in case the  
56 sources are not homogeneous (Dumortier, Aubinet, Lebeau, Naiken, & Heinesch,  
57 2019). The main methodologies that have been used to address this kind of sources

58 in similar applications, such as cattle feedlots, are micrometeorological techniques and  
59 wind tunnel methods (Misselbrook, Nicholson, Chambers, & Johnson, 2005).  
60 Micrometeorological techniques such as the integrated flux method (Denmead, 1983)  
61 and dispersion models (Bonifacio et al., 2012; Flesch, Wilson, Harper, Crenna, &  
62 Sharpe, 2004) have proven to be very effective in back calculating emission fluxes  
63 from open field emission sources. These systems, however, despite their large range  
64 of application, have the common disadvantage of being unsuited to estimate emissions  
65 from sources, such as the outdoor runs, which are in proximity of multiple other sources  
66 of the same pollutant (e.g. barn, manure storage facilities etc.), due to cross  
67 interference. Wind tunnels are enclosure systems which have been widely used to  
68 assess PM and gaseous emissions from soil or other ground level area sources  
69 (Dinuccio, Gioelli, Balsari, & Dorno, 2012; Gao et al., 2020; Kabelitz et al., 2020) and  
70 allow to monitor the emissions, gathering data under standardized wind speed  
71 conditions. Aarnink, Hol, & Beurskens (2006) used a ventilated chamber technique to  
72 assess ammonia (NH<sub>3</sub>) emissions from outdoor runs in laying hen houses, but did not  
73 address PM emissions. The main constraint regarding the use of a classical wind  
74 tunnel method to assess emissions from outdoor runs is linked with the hens behavior.  
75 In fact, hens often engage in dust bathing behavior, which was recognized as a form  
76 of personal hygiene and also as a social behavior which has beneficial effects on  
77 animal welfare (Abrahamsson, Tauson, & Appleby, 1996; van Liere, Kooijman, &  
78 Wiepkema, 1990; Vestergaard, Skadhauge, & Lawson, 1997). When hens dustbathe  
79 in outdoor runs soil, they can cause soil (re)suspension in the air leading to PM  
80 emissions. Therefore, in order for a wind tunnel to effectively assess outdoor runs PM  
81 emissions, it should allow to assess the emission deriving from dustbathing and other  
82 hen activities.

83 The main aim of this work is to develop a multi-step methodology to assess outdoor  
84 runs emissions of PM and identify the role of hens behavior and soil moisture as main  
85 drivers of the emission. A wind tunnel prototype was designed to allow the hens to  
86 enter it willingly and dustbathe inside of it, in order to assess the effect of hen density  
87 (HD, hens m<sup>-2</sup>) on the emissions. Moreover, the emission potential of the outdoor run  
88 soil was assessed, using a Soil Resuspension Chamber (SRC) method to assess the  
89 effect of soil humidity on PM release. The gathered information, combined with daily  
90 meteorological data and evapotranspiration (ET) modelling, was utilized to assess PM  
91 emissions over a 1-year period.

92 The gathered results will allow to acquire a better understanding of poultry generated  
93 PM emissions by addressing some of the main factors driving PM formation from free  
94 range areas in poultry houses. Moreover, it will provide a new perspective on hens  
95 behavior, addressing its influence on PM emissions.

96

## 97 **2. Materials and methods**

98

### 99 *2.1. Wind tunnel design*

100 Wind tunnels used for PM and gaseous emission assessments have a wide variety of  
101 shapes, but they usually share some common elements. They are built in sturdy  
102 material, such as plastic or stainless steel, they have a main chamber, which has the  
103 purpose of enclosing the studied area source, and they are provided with input and  
104 output pipes. The wind speed inside the tunnel ( $WS_{\text{tunnel}}$ , m s<sup>-1</sup>) is generated using a  
105 ventilator and normally set to a value that matches the average outdoor wind speed  
106 (Dinuccio et al., 2012). The pollutant concentrations (mg m<sup>-3</sup>) are normally monitored

107 through sampling ports placed on the inlet and outlet pipe. The emission rate (ER, mg  
108 m<sup>-2</sup> hr<sup>-1</sup>) is then calculated as follows:

$$109 \quad ER = \frac{(C_{out} - C_{in}) WT_{flow}}{A}$$

110 Where  $C_{out}$  (mg m<sup>-3</sup>) is the outlet concentration,  $C_{in}$  is the background concentration  
111 (mg m<sup>-3</sup>),  $WT_{flow}$  is the total airflow passing through the tunnel (m<sup>3</sup> hr<sup>-1</sup>), and  $A$  is the  
112 enclosed area (m<sup>2</sup>).

113 The wind tunnel design proposed for assessing emissions from outdoor runs in poultry  
114 follows the same concept as described above, but it was modified to allow the  
115 assessment of emissions caused by dustbathing hens. To do so the inlet pipe was  
116 removed and the front of the tunnel was left open in order to allow the hens to walk in.  
117 The main chamber of the tunnel was built using a solid metal framework and wrapping  
118 a transparent plastic foil around it. This solution was adopted to allow sunlight to enter  
119 the tunnel, since the hen's behavior is affected by light. The funnel structure connecting  
120 the main chamber to the pipe was constituted by an iron wire framework covered by  
121 the same plastic foil covering the tunnel. Moreover, a metal grid was placed in between  
122 the main chamber and the funnel structure to prevent the hens from entering the funnel  
123 structure or the pipe. A ventilator with a 35 cm diameter was used (VOSTERMANS,  
124 Multifan IP 55 KLF). The overall design of the wind tunnel is illustrated in Figure 1.

125 The final design choices were forced by the necessity of allowing hens to dustbathe  
126 inside the wind tunnel. Similar designs were previously adopted by Balsari et al. (2006),  
127 for assessing ammonia emissions after manure spreading and by Roney et al. (2006)  
128 for fugitive dust emissions from soil. While similar in the overall design, the wind tunnel  
129 adopted by those two authors relied on different solutions for measuring the outlet  
130 concentration. To validate the wind tunnel design for emission assessment and to

131 define a suitable concentration sampling strategy, a laboratory test was carried out  
132 using a tracer gas to test the tunnel capture efficiency. The wind tunnel flow and  
133 internal wind speed were also characterized under laboratory conditions.

134

135 *2.2. Wind tunnel flow, internal wind speed and expected environmental wind*  
136 *speed*

137 The flow of the tunnel was assessed by measuring, using a hotwire anemometer  
138 (Testo, 435), the wind speed ( $\text{m s}^{-1}$ ) at the inlet of the ventilator pipe in 5 different  
139 positions and multiplying it by the section area of the pipe ( $116.2 \text{ cm}^2$ ).

140 The tunnel wind speed was set in order to match the external wind speed in the poultry  
141 farm area. The average external wind speed at 0.2 m meters from ground level was  
142 estimated, using the mean wind speed data retrieved from KNMI Deelen weather  
143 station (KNMI, 2020), according to the following formula:

144 
$$ExpWS_{(0.2 \text{ m})} = WS_{(10 \text{ m})} \frac{\ln(0.2/z_0)}{\ln(10/z_0)}$$

145 Where  $ExpWS_{(0.2 \text{ m})}$  is the external mean wind speed at 0.2 m height from ground level,  
146  $WS_{(10 \text{ m})}$  is the mean wind speed (average of hourly wind speed data for year 2020;  $4.1$   
147  $\text{m s}^{-1}$ ) at 10 m from ground level (measured at Deelen station), and  $z_0$  is the roughness  
148 length (set to 0.01). The equation used is explained in detail by Stull (2012).

149 The wind speed inside the tunnel was assessed by using the same hotwire  
150 anemometer, attached on a tripod (at 0.2m from the ground) and placed in 8 different  
151 positions inside the tunnel. The fan rotational speed was regulated using an external  
152 regulator (Stienen, SPM-6).

### 2.3. Assessment of Wind Tunnel capture efficiency

The capture efficiency of the WT was tested through a tracer gas experiment, using pure ammonia as tracer (the setup is shown in Figure 1). Ammonia was released from a cylinder and emitted inside the tunnel from a 30 cm long line source, constituted by a dead-end Teflon tube (4 mm  $\varnothing$ ), which had holes (performed with a 3 mm  $\varnothing$  drill) every 10 cm. The line source was placed perpendicularly to the WT flow at 20 cm from the WT entrance. The  $\text{NH}_3$  flow was regulated using a mass flow controller (Bronkhorst, EL-FLOW<sup>®</sup>), which was set at three flow levels F1, F2 and F3. The mass flow regulator was calibrated for the regulation of atmospheric airflow, therefore the amount of  $\text{NH}_3$  emitted with the three flow settings (F1, F2 and F3) utilized had to be assessed in a further laboratory experiment. A scheme of the experimental layout is shown in Figure 2. The assessment consisted in fluxing the ammonia into an acid bottle, capped with an impinger, which contained 0.5 molar  $\text{HNO}_3$  acid. A flow meter was connected to the outlet of the impinger to check whether all ammonia was captured by the acid solution. A safety outlet tubing was placed at 2 m height to prevent exposure for the operator. The experiment was repeated twice for each flow level and the fluxing time was 4 minutes per sample. The collected acid samples were then analysed for the  $\text{NH}_4\text{-N}$  content ( $C_{\text{N-NH}_4}$ ,  $\text{mg L}^{-1}$ ). During the experiment the formation of a negative pressure inside the acid bottle was observed, especially at low pressure from the ammonia tank. This caused a pressure deficit, affecting the flow passing through the system. This issue was due to the height difference among the system outlet (2 m height) and the impinger (at ground level). To solve this imbalance, a correction factor (cf) was calculated by measuring, using a flow meter, the incoming and the outgoing flow to the impinger. This later assessment was performed using water in place of the acid and pressured air instead of ammonia, for safety reasons.



178 The amount of ammonia captured with the impinger method ( $I_{NH_3}$ , mg) at the three flow  
179 levels was then assessed according to the following formula:

$$180 \quad I_{NH_3} = C_{N-NH_4} L \frac{NH_3 M_{mass}}{N M_{mass}} cf$$

181 Where  $L$  is the amount of acid solution in the impinger bottle (L),  $NH_3 M_{mass}$  and  $N M_{mass}$   
182 are the molar masses of  $NH_3$  and N (g/mol) respectively and  $cf$  was found to be 1.3  
183 ( $\pm 0.21$ ), 1.09 ( $\pm 0.18$ ) and 1.04 ( $\pm 0.17$ ) for F1, F2 and F3 respectively.

184 During the capture efficiency test, the ammonia concentration at the outlet and inlet of  
185 the tunnel ( $mg\ m^{-3}$ ) was measured using electrochemical sensors (Polytron® 8100 EC,  
186 Dräger). The outlet concentration was measured in three different sampling points (S1,  
187 S2 and S3, as shown in Figure 1). The concentration measurements lasted 15 minutes  
188 for each of the  $NH_3$  flows and sampling point combinations, for a total of 135 minutes.  
189 The observed concentrations were then averaged over three minutes time intervals  
190 and used to calculate the total amount of ammonia captured by the WT system ( $WT_{NH_3}$ ,  
191 mg), according to the following formula:

$$192 \quad WT_{NH_3} = (C_{out} - C_{in}) WT_{flow} T$$

193 Where  $C_{out}$  ( $mg\ m^{-3}$ ) is the outlet concentration measured in S1, S2 and S3,  $C_{in}$  is the  
194 background ammonia concentration ( $mg\ m^{-3}$ ),  $WT_{flow}$  is the wind tunnel flow ( $m^{-3}\ s^{-1}$ )  
195 and  $T$  is the time (s) of the experiment. It was assumed that the PM particles are  
196 transported by the air flow in a similar way as  $NH_3$ , as previously done by other authors  
197 (Maffia, Dinuccio, Amon, & Balsari, 2020; Pattey & Qiu, 2012), and that the capture  
198 efficiency remains the same.

#### 199 2.4. Field measurement protocol for wind tunnel trials

200 Field measurements were performed in a free range laying hen house sited in the  
201 Netherlands (52°05'58.6"N 5°34'38.2"E), in an area characterized by sandy soils. The  
202 farm is provided with a large outdoor area and the hens are allowed out from 10 am till  
203 sunset. The wind tunnel equipment was placed at 6 m from the barn, inside of the area  
204 where, according to Niekerk et al. (2016), most of the hens stand when outside. The  
205 measurements were performed, on sunny days, twice a week for 1 month and a short  
206 period was needed for the hens to adapt to the tunnel and start entering inside. Each  
207 measurement event lasted 3-4 hours and the hens were left free to enter the tunnel  
208 at will. Concentration measurements were performed using optical particle counters  
209 (DustTrak II, TSI) for PM<sub>10</sub> measuring both at the inlet and the outlet (position S3) of  
210 the tunnel. The measuring frequency was of one measurement every 10 seconds. The  
211 two instruments were compared before the experiment, by measuring for 6 h in the  
212 same spot, and gave consistent results.

213 The first measurement was made with a  $0.95 \text{ m}^3 \text{ s}^{-1}$  WT<sub>flow</sub>, which generates a wind  
214 speed inside the tunnel more similar to the actual wind conditions in the region. Then,  
215 since it was observed that the hens preferred to enter the tunnel under slightly lower  
216 wind speed conditions, WT<sub>flow</sub> was set at  $0.73 \text{ m}^3 \text{ s}^{-1}$ . Being that this work aims mainly  
217 to assess PM emissions deriving from hens activity and that those emissions are  
218 predominantly caused by mechanical resuspension of soil, it was assumed that having  
219 a slightly lower wind speed as compared to the natural one is acceptable. The ERs  
220 were calculated with the same method used for the wind tunnel efficiency assessment,  
221 described in section 2.3, expressing the emissions as  $\text{mg m}^{-2} \text{ hr}^{-1}$ .

222 A video camera (HERO 7 Silver, GoPro) was placed inside the tunnel to observe hens  
223 activity and count the number of hens inside the tunnel. This was necessary to relate

224 the obtained ERs to the hen density (HD, hens m<sup>-2</sup>hr<sup>-1</sup>), which was calculated as  
225 follows:

$$226 \quad HD = \frac{N_{hens}}{A}$$

227 Where N<sub>hens</sub> is the number of hens present inside the tunnel and A is the enclosed area  
228 (m<sup>2</sup>).

229 When the hen density was over 3.2 hens m<sup>-2</sup> (5 hens inside the tunnel at the same  
230 time), the density was considered simply as >3.2 hens m<sup>-2</sup>, since, due to fouling of the  
231 tunnel, it was impossible to distinguish the exact number of hens.

232 The ERs were then averaged over the HD, in order to obtain a dataset with an average  
233 ER for each HD category (0.6, 1.3, 1.9, 2.6, 3.2, >3.2 hens m<sup>-2</sup>) for each measurement  
234 event. Each HD category correspond to an exact number of hens inside the tunnel (1,  
235 2, 3, 4, 5 and >5 hens).

236 The soil moisture content on each measuring day was assessed by collecting a soil  
237 sample inside the tunnel, before and after the measurement, and assessing soil  
238 humidity with a gravimetric method by drying in a hoven at 105°C for 24 h.

239

## 240 *2.5. Soil resuspension chamber experiment to determine soil moisture effect*

241 A soil resuspension chamber (SRC), which has been fully described in a previous  
242 paper (Padoan, Maffia, Balsari, Ajmone-Marsan, & Dinuccio, 2021), was used to  
243 resuspend the outdoor run soil. The chamber was composed of a rotating drum, with  
244 a 25 L capacity, and a rotation frequency of 26 revolutions per minute, powered by an  
245 electric engine with 0,75 kW of power and an electric potential of 220 V. During the  
246 trials, the drum was closed by a flange, on which were nested four flexible PVC tubes

247 (0.4 m long with 8 mm diameter), provided with a series of small holes (diameter 0.3  
248 mm), allowing clean air inside the rotating drum. The air was sucked from the drum  
249 through an aspiration pipe, which pulled the emitted dust towards a deposition  
250 chamber. A vane pump (5; VTE3, Rietschle) was used to draw the air from the  
251 deposition chamber and induced an air flow of 30 L min<sup>-1</sup> through the system. The re-  
252 suspended particulate matter was sampled, through a sampling port, using both an  
253 optical PM monitor (Grimm 11-D, Grimm Aerosol Technik), to assess particle quantity.  
254 A scheme of the system is provided in Figure 3.

255 Soil samples (three replicas per each soil humidity level) were resuspended by placing  
256 a soil aliquot inside the SRC rotating drum for 15 min. The experiments were conducted  
257 using soil samples of 5 g. The emission potential (EP, mg kg<sup>-1</sup>) was defined at four  
258 different moisture contents (calculated as 0, 15, 30 and 40%, by weight, of the soil field  
259 capacity). Soil EP (mg kg<sup>-1</sup>) was calculated as follows:

$$260 \quad EP = \frac{C}{1000} * \frac{Q * t}{S}$$

261 Where C is the particle concentration (µg m<sup>-3</sup>) measured with the Grimm PM monitor,  
262 Q is the SRC airflow (m<sup>3</sup> min<sup>-1</sup>), calculated as the sum of the pump and the flow of the  
263 Grimm internal pump (1.2 L min<sup>-1</sup>), S is the soil sample mass (kg), and t the considered  
264 time-span (min).

265 A detailed description of the sampling systems and intervals is provided in Padoan et  
266 al. (2021) Soil emission potentials were calculated in terms of PM<sub>10</sub>, PM<sub>4</sub> and PM<sub>2.5</sub>.

267

268 *2.6. Soil humidity estimation and PM<sub>10</sub> emission estimation over one year period*

269 Soil humidity was assessed on the base of weather data, applying a water balance  
270 approach. The soil water balance was calculated by applying the Hargreaves–Samani  
271 equation (HS, Hargreaves & Samani, 1985) to calculate the potential  
272 evapotranspiration (ET<sub>0</sub>). The HS method was chosen since it is, among the simplified  
273 ET estimation methods, the one that finds better agreement with the Penman-Monteith  
274 recommended method from FAO 56 (Allen, Pereira, Smith, Raes, & Wright, 2005). The  
275 HS equation applied for this study is as follow:

$$276 \quad ET_0 = K_{HS}K_T(T_a + 17.78)(T_{max} - T_{min})^{0.5}R_a$$

277 Where  $K_{HS}$  and  $K_T$  are dimensionless coefficients,  $T_a$  is the average daily temperature  
278 (°C),  $T_{max}$  is the maximum daily temperature (°C),  $T_{min}$  is the minimum daily  
279 temperature and  $R_a$  is the extra-terrestrial radiation (mm day<sup>-1</sup>).

280  $T_a$ ,  $T_{max}$ ,  $T_{min}$  and  $R_a$  where derived from nearby KNMI weather stations located in  
281 Deelen (2019 dastaset).

282 The actual evapotranspiration ET<sub>c</sub> was then derived by multiplying ET<sub>0</sub> by the  
283 coefficient  $K_c$  (which was set to 1.1 for bare soil conditions). The soil water content  
284 (WC, mm) was then calculated, considering a soil depth of 15 cm, as follows:

$$285 \quad WC = WC_i + Rain - (ET_c * k_s) - LW$$

286 Where Rain is the daily rainfall (mm),  $k_s$  is the stress coefficient (derived as in Allen et  
287 al., 2005), LW is the leaching water (mm) and  $WC_i$  is the soil water content at the start  
288 of the day (WC the first day of the series was set to FC, since it was after a heavy rain  
289 event). LW was calculated as the difference among  $WC_i$ , net of the ET flux, and soil  
290 Field capacity.

291 The 15 cm depth of soil considered was selected observing the average depth of ridges  
292 caused by hens activity in the outdoor run area. Soil physical characteristics and field

293 capacity were experimentally assessed. Fifteen subsamples of soil were taken by  
294 applying a X sampling scheme (Colombo & Miano, 2015). The topsoil subsamples  
295 were collected to a depth of 15 cm, which was considered the depth interested by hens  
296 dustbathing activities. Field capacity was determined for each soil according to the  
297 official method proposed by MiPAF (1997) and soil texture was defined according to  
298 the Soil Science Division Staff (2017) guidelines.

299 Finally, the daily emissions ( $E_d$ ,  $\text{mg m}^{-2} \text{d}^{-1}$ ) were calculated by integrating soil emission  
300 potential (as affected by humidity) and outdoor run emission level, according to the  
301 following equation:

$$302 \quad E_d = \frac{EP_d ER_{HD}}{EP_{WT}} H$$

303 Where,  $EP_d$  ( $\text{mg kg}^{-1}$ ) is the emission potential related to the soil moisture conditions  
304 of the day,  $ER_{HD}$  is the emission rate ( $\text{mg m}^{-2} \text{hr}^{-1}$ ) calculated on the base of the HD  
305 expected on the specific day,  $EP_{WT}$  ( $\text{mg kg}^{-1}$ ) is the emission potential related to the  
306 moisture conditions occurred during the wind tunnel trials and H is the number of hours  
307 in which hens are allowed outside.

308 The HD expected on each specific day was estimated on basis of literature information.  
309 The few studies available on this topic reported very different data regarding the  
310 number of hens (% on total flock consistence), ranging from around 10 to 40%  
311 (Gebhardt-Henrich, Toscano, & Fröhlich, 2014; Hegelund, Sørensen, Kjaer, &  
312 Kristensen, 2005; Hirt & Zeltner, 2000). This large variability is due to several aspects  
313 that influence hens behavior and their usage of outdoor spaces. The main influencing  
314 parameters are the flock size (Gebhardt-Henrich et al., 2014), the environmental  
315 conditions (Pettersson, Freire, & Nicol, 2016) and the presence of sheltering structures  
316 in the outdoor run (E. Zeltner & Hirt, 2003; Esther Zeltner & Hirt, 2008). Moreover, most

317 of free ranging hens (60-95%) tend to graze in the first 20 m from the outdoor run,  
318 causing complete destruction of the canopy in that area (Fürmetz, Keppler, Knierim,  
319 Deerberg, & Heß, 2005). The farm in which this study was performed had a large flock  
320 size (24,000 hens) and an outdoor area of 9.6 ha. On basis of this information, it was  
321 considered that only 20% of laying hens are found outside at one moment and 80% of  
322 those are found in the over grazed area at short distance from the house. This area,  
323 presented in Figure 4, was measure to be equal to 6,263 m<sup>2</sup>. Therefore, the emission  
324 from the overgrazed area of the outdoor run was assessed considering an average HD  
325 of 0.6 hens m<sup>-2</sup>. The number of hours in which the hens were let outside (7 h in winter  
326 and 11 h in summer) was also considered when assessing the daily emission.

327

## 328 *2.7. Statistical analysis*

329 Statistical analyses were performed to test the fluxes of NH<sub>3</sub> observed during the wind  
330 tunnel efficiency estimation trial, with the 3 concentration sampling position (S1, S2,  
331 S3), as compared to the actual amount of ammonia released from the ammonia vessel  
332 determined with the impinger method ( $I_{NH_3}$ ). A two-way ANOVA procedure, performed  
333 using the R statistical software (R core team, 2019), followed by a Bonferroni post-hoc  
334 test, was used. Observed differences were considered significant for  $P < 0.05$ . A linear  
335 regression was applied to investigate the relation between the natural logarithm of  
336 PM<sub>10</sub> ER and HD and that between EP and soil water content.

337

## 338 **3. Results**

### 339 *3.1. Wind tunnel flow and wind speed charts*

340 The first flow rate tested was of  $0.95 \pm 0.01 \text{ m}^{-3} \text{ s}^{-1}$ , leading to a wind speed of  $1.8 \pm 0.03$ ,  
341 which matches the expected wind speed of the area ( $\text{ExpWS}_{(0.2 \text{ m})} = 1.8 \text{ m s}^{-1}$ ). Since  
342 the hens were reluctant to enter the tunnel at this high windspeed, a lower flow rate of  
343  $0.73 \pm 0.01 \text{ m}^{-3} \text{ s}^{-1}$  was used, leading to an average wind speed inside the tunnel of  
344  $1.5 \pm 0.11 \text{ m s}^{-1}$ . The average wind speed inside the tunnel was measured at 8  
345 positions, at 0.20 m height, and resulted in higher values in the central row and slightly  
346 lower values in the side rows (Figure 5). At the tunnel inlet the wind speed was less  
347 evenly distributed than in the central and back portion of the tunnel.

348

### 349 3.2. *Assessment of WT capture efficiency*

350 The ammonia concentration observed during the wind tunnel validation test, as  
351 measured in S1, S2 and S3, with F1, F2 and F3  $\text{NH}_3$  flows are summarized in Figure  
352 6. The observed concentration varied slightly among the three sampling points. It was  
353 also highlighted that the standard deviation of the results obtained from measurements  
354 in S3 is lower than those of S1 and S2, allowing for a steadier signal.

355 Table 1 shows the results of the ANOVA comparing the amount of ammonia emitted  
356 from the cylinder ( $I_{\text{NH}_3}$ ), assessed with the impinger method, and the amount detected  
357 with the wind tunnel,  $\text{WT}_{\text{NH}_3}$ , in the three sampling positions. The  $\text{WT}_{\text{NH}_3}$  observed in  
358 S2 and S3 does not differ significantly from  $I_{\text{NH}_3}$  with all the flux levels tested. The S1  
359 assessment is instead significantly lower than expected at maximum  $\text{NH}_3$  flow level.

360

### 361 3.3. *Results of wind tunnel assessments*



362 The average PM<sub>10</sub> ER calculated as a result of the field trials was equal to 100.2 ± 26.4  
363 mg m<sup>-2</sup> hr<sup>-1</sup>.

364 The linear regression analysis showed that HD had a significant (P<0.05) effect on the  
365 logarithm of PM<sub>10</sub> emissions, showing a linear correlation (Figure 7). This means that  
366 the increase of HD causes an exponential increase of the ERs. It is possible to identify  
367 a function that allows to estimate the ER on basis of HD, as follows:

$$368 \quad ER = e^{(0.94 HD + 2.14)}$$

369 Where the intercept value (2.14) accounts for the effect of wind erosion and the slope  
370 value (0.94) accounts for the effect of HD. The linear model shows a good fit (R<sup>2</sup> =  
371 0.76). In general, PM<sub>10</sub> emissions ranged from 10.5 ± 2.1 mg m<sup>-2</sup> hr<sup>-1</sup> (with HD =  
372 0 hens m<sup>-2</sup>) to 170.7 ± 47.1 mg m<sup>-2</sup> hr<sup>-1</sup> (with HD = 3.2 hens m<sup>-2</sup>).

373 Soil humidity was found to be equal to 0.84 ± 0.14 % (on mass) and remained almost  
374 constant throughout the experiment, due to the presence of the tunnel, which  
375 prevented the precipitations to reach the enclosed soil.

376

377

#### 378 *3.4. Effect of soil moisture on PM emission potential*

379 The emission potentials curves for outdoor run soil, as well as the soil textural  
380 components, are presented in Figure 8. It can be observed that the EP decreases  
381 exponentially with the increase of soil water content. The regression curves were able  
382 to describe the EP trend with good fit and the overall results are similar to those  
383 presented by previous authors who adopted similar methods to study the effect of soil  
384 moisture on soils' EP (Carvacho, Ashbaugh, Brown, & Flocchini, 2004; Funk, Reuter,

385 Hoffmann, Engel, & Öttl, 2008; Madden, Southard, & Mitchell, 2009, 2010). It was also  
386 observed that of the soil emitted as PM<sub>10</sub> 56% and 17% is in the PM<sub>4</sub> and PM<sub>2.5</sub> ranges  
387 respectively. The soil texture in the study farm was Sandy (92% sand, 5% silt and 2%  
388 clay).

389

### 390 *3.5. Estimated PM emissions from overgrazed area of outdoor runs*

391 The information gathered on the effect of HD and soil moisture on PM<sub>10</sub> emissions,  
392 coupled with meteorological data, allowed to provide a first estimation of daily PM<sub>10</sub>  
393 emissions from the overgrazed areas of outdoor runs. The estimated E<sub>d</sub> were averaged  
394 on a monthly basis and are presented, together with monthly rainfall (mm) and ET  
395 fluxes (mm), in Figure 9. The average gravimetric soil water content was maximum in  
396 January (14%) and rapidly decreased in April, reaching its minimum value in July (7%),  
397 then it rose again from September. PM emissions were highly seasonal, with higher  
398 emissions occurring in the central months of the year. The total PM<sub>10</sub> emissions over  
399 2019, as estimated with the simplified procedure described in paragraph 2.6, were of  
400 12.5 g m<sup>-2</sup> yr<sup>-1</sup> (this estimation is referred only to the overgrazed area of the outdoor  
401 run, 6263 m<sup>2</sup>).

402

## 403 **4. Discussion**

404

### 405 *4.1. Wind tunnel validation: internal wind speed and capture efficiency*

406 The results showed a slightly uneven distribution of the wind speed inside the tunnel.  
407 This is due to the friction effect of the tunnel walls and to the turbulence created by the

408 funnel structure leading to the outlet pipe. The variations observed are consistent with  
409 those observed by Balsari et al. (2006, 2007), who adopted a similar wind tunnel  
410 design. The average wind speed inside the tunnel, of approx.  $1.5 \text{ m s}^{-1}$ , is only slightly  
411 lower than the expected WS at that height ( $1.8 \text{ m s}^{-1}$ ), calculated on basis of the 10 m  
412 average annual wind speed of the location where the measurements were done  
413 (approx.  $4.1 \text{ m s}^{-1}$ ; KNMI, 2020). It was preferred to set a slightly lower wind speed  
414 since it was observed that the hens were more comfortable with this lower flow rate  
415 than with higher ones. Moreover, the hens normally gather around obstacles and trees,  
416 which act as repairs against the wind. In fact, the surface roughness effect, as well as  
417 the presence of natural obstacles, drastically reduce the wind speed at ground level  
418 (Stull, 2012).

419 Observing the results of the wind tunnel validation test (Table 1) it appears that both  
420 S2 and S3 sampling solutions are suitable for measurement and show a good  
421 agreement with the impinger method assessment. The  $WT_{\text{NH}_3}$  observed in S2 and S3,  
422 in fact, did not differ significantly from  $I_{\text{NH}_3}$  with all the flux levels tested. At S1, however,  
423  $\text{NH}_3$  concentrations were significantly lower than expected from  $I_{\text{NH}_3}$  at maximum  $\text{NH}_3$   
424 flow level.

425 Nonetheless, the S3 sampling point appears to perform more consistently and provide  
426 data with lower standard variation (as highlighted in Figure 6). Moreover, the S2  
427 sampling solution is not suitable for PM measurements, since the DustTrak instrument  
428 is not designed for isokinetic sampling and, therefore, is not suited for measurement  
429 inside a pipe with a strong airflow. It was noticed that the average values derived from  
430 the measurements in S3 were slightly higher than the expected ones ( $I_{\text{NH}_3}$ , as shown  
431 in Table 1), but the difference was not statistically significant. In conclusion, the S3

432 sampling point performed better than S1 and S2 and was identified as the best option  
433 to determine the emissions.

434

#### 435 *4.2. Influence of hen density and soil moisture on particulate matter emissions*

436 The first field assessments allowed to estimate PM<sub>10</sub> emissions from hens outdoor  
437 activities, which were found to be equal to  $100.2 \pm 26.4 \text{ mg m}^{-2} \text{ hr}^{-1}$ . It has been also  
438 shown that dust emissions were affected by the density of hens in the outdoor runs. In  
439 fact, when HD increased PM<sub>10</sub> emissions increased exponentially. The obtained ELs  
440 must be referred to the particular soil humidity conditions monitored during the  
441 experiment, which were extremely dry. Since, as highlighted by Funk et al. (2008), dry  
442 soil conditions lead to high PM emissions, the ERs calculated in these first field  
443 assessments should be considered as emission potentials, indicating the maximum  
444 amount of PM<sub>10</sub> that can be derived from the outdoor runs in critical environmental  
445 conditions.

446

#### 447 *4.3. Influence of soil moisture on particulate matter emission potential*

448 The exponential decrease of soil emission potential with increasing soil water content,  
449 observed during SRC experiment is in agreement with previous findings (Carvacho et  
450 al., 2004; Madden et al., 2009, 2010; Padoan et al., 2021). Moreover, previous  
451 researches showed that soil texture is a crucial factor in influencing EP and  
452 hydrological properties of soil. According to these findings, the very high sand % of the  
453 soil analyzed in this study, could have led to a lower maximum EP level in dry soil  
454 condition. Nonetheless, a more compact soil usually has more capacity to retain water

455 and a higher field capacity, being less prone to the dryer conditions that are necessary  
456 for PM<sub>10</sub> to be emitted.

457

#### 458 4.4. *Estimation of PM emissions over a 1-year period*

459 The estimated PM<sub>10</sub> emission fluxes were highly seasonal, with most of PM losses  
460 occurring during the central months of the year. This is attributable to the higher  
461 temperatures and lower precipitation, which promote dry soil condition and favor PM  
462 formation. The estimated emissions for overgrazed outdoor run areas were of  
463 12.5 g m<sup>-2</sup> yr<sup>-1</sup>. These emissions, if divided for the total number of hens reared in the  
464 farm, are equal to 8.9 mg hen<sup>-1</sup> d<sup>-1</sup>. Cambra-López et al. (2009) reported, in their  
465 assessment of PM<sub>10</sub> emissions from indoor poultry houses, emissions up to 146.9 mg  
466 hen<sup>-1</sup> d<sup>-1</sup>. Therefore, PM<sub>10</sub> emitted from outdoor spaces appears to be lower than that  
467 deriving from the indoor areas of the farm. Nonetheless, since the hens are using only  
468 a small portion of the outdoor area, their activity causes significant degradation of soil,  
469 with formation of furrows where hens gather to dustbathe. The concentration of many  
470 hens on little space can lead to other environmental issues linked with the  
471 concentration of nutrients on small areas (Menzi, Katz, Fahrni, Neftel, & Frick, 1998).  
472 Therefore, measures to favor the usage of a bigger portion of outdoor runs by hens  
473 should be implemented.

474 More studies should be performed to provide precise assessments of the usage of  
475 outdoor spaces by hens and identify the main factors influencing it, since current  
476 information is insufficient. The parametrization of average HD through the year is, in  
477 fact, the main drawback of the estimation technique used for assessing emissions.

478 Moreover, since PM emissions from soil are also strongly affected by wind speed  
479 conditions (Avecilla, Panebianco, & Buschiazzo, 2017)

480 , improvements should be made also in the parametrization of this factor, through  
481 further wind tunnel experiments.

482

## 483 **5. Conclusions**

484 A wind tunnel method to assess the effect of hen density on PM emission from outdoor  
485 runs in free range laying hens houses was successfully developed. The methodology  
486 allowed to measure PM emissions levels from hens activity and to study the influence  
487 of hens behavior on the emissions. HD influences PM<sub>10</sub> emissions, causing them to  
488 increase exponentially when a higher number of animals are present per surface area  
489 unit ( $ER = e^{(0.94 HD+2.14)}$ ). The emission fluxes deriving from the outdoor runs under dry  
490 soil conditions, ranged from  $10.5 \pm 2.1 \text{ mg m}^{-2} \text{ hr}^{-1}$  (with  $HD = 0.0 \text{ hens m}^{-2}$ ) to  $170.7 \pm$   
491  $47.1 \text{ mg m}^{-2} \text{ hr}^{-1}$  (with  $HD = 3.2 \text{ hens m}^{-2}$ ).

492 A laboratory experiment allowed to assess the effect of soil moisture on the emissions,  
493 deriving emission potential (EP,  $\text{mg kg}^{-1}$ ) curves, showing an exponential decrease of  
494 EP with increasing soil moisture. This information allowed to scale the emission levels  
495 assessed with the wind tunnel, according to soil water content, estimated with a soil  
496 water balance procedure and averaged on a daily basis. An estimation of PM<sub>10</sub>  
497 emission occurring from the overgrazed areas of outdoor runs was provided and  
498 resulted equal to  $12.5 \text{ g m}^{-2} \text{ yr}^{-1}$ . These emissions, if divided for the total number of  
499 hens reared in the farm, are equal to  $8.9 \text{ mg hen}^{-1} \text{ d}^{-1}$ , while EF for indoor poultry farms  
500 in literature are up to  $146.9 \text{ mg hen}^{-1} \text{ d}^{-1}$ . Therefore, PM<sub>10</sub> emitted from outdoor spaces  
501 is less of a concern than in-house emissions. Nonetheless, by using only a small

502 portion of the outdoor area, hens activity can cause significant degradation of soil, with  
503 formation of furrows where hens gather to dustbathe. Therefore, new solutions should  
504 be implemented to face this issue and to favor the spreading of hens on larger  
505 surfaces.

506

507

## 508 **Acknowledgements**

509 Funding: This study has been funded by the Ministry of Infrastructure and Water  
510 Management of the Netherlands.

511

## 512 **6. References**

513

514 Aarnink, A. J. A., Hol, A. M. G., & Beurskens, A. G. C. (2006). Ammonia emission  
515 and nutrient load in outdoor runs of laying hens. *Netherlands Journal of*  
516 *Agricultural Science*, 54(2), 223–234.

517 Abrahamsson, P., Tauson, R., & Appleby, M. C. (1996). Behaviour, health and  
518 integument of four hybrids of laying hens in modified and conventional cages.  
519 *British Poultry Science*, 37(3), 521–540.

520 <https://doi.org/10.1080/00071669608417882>

521 Allen, R. G., Pereira, L. S., Smith, M., Raes, D., & Wright, J. L. (2005). FAO-56 Dual  
522 Crop Coefficient Method for Estimating Evaporation from Soil and Application  
523 Extensions. *Journal of Irrigation and Drainage Engineering*, 131(1), 2–13.

524 [https://doi.org/10.1061/\(ASCE\)0733-9437\(2005\)131:1\(2\)](https://doi.org/10.1061/(ASCE)0733-9437(2005)131:1(2))

525 Avecilla, F., Panebianco, J. E., & Buschiazzo, D. E. (2017). Meteorological conditions  
526 during dust (PM 10 ) emission from a tilled loam soil: Identifying variables and  
527 thresholds. *Agricultural and Forest Meteorology*, 244–245, 21–32.  
528 <https://doi.org/10.1016/j.agrformet.2017.05.016>

529 Bonifacio, H. F., Maghirang, R. G., Auvermann, B. W., Razote, E. B., Murphy, J. P., &  
530 Harner, J. P. (2012). Particulate matter emission rates from beef cattle  
531 feedlots in Kansas—Reverse dispersion modeling. *Journal of the Air & Waste*  
532 *Management Association*, 62(3), 350–361.  
533 <https://doi.org/10.1080/10473289.2011.651557>

534 Borlée, F., Yzermans, C. J., Aalders, B., Rooijackers, J., Krop, E., Maassen, C. B. M.,  
535 ... Smit, L. A. M. (2017). Air Pollution from Livestock Farms Is Associated with  
536 Airway Obstruction in Neighboring Residents. *American Journal of Respiratory*  
537 *and Critical Care Medicine*, 196(9), 1152–1161.  
538 <https://doi.org/10.1164/rccm.201701-0021OC>

539 Cambra-López, M., Winkel, A., Harn, J. van, Ogink, N. W. M., & Aarnink, A. J. A.  
540 (2009). Ionization for reducing particulate matter emissions from poultry  
541 houses. *Transactions of the ASABE / American Society of Agricultural and*  
542 *Biological Engineers*, 52(5), 1757–1771.

543 Cambra-López, María, Aarnink, A. J. A., Zhao, Y., Calvet, S., & Torres, A. G. (2010).  
544 Airborne particulate matter from livestock production systems: A review of an  
545 air pollution problem. *Environmental Pollution (Barking, Essex: 1987)*, 158(1),  
546 1–17. <https://doi.org/10.1016/j.envpol.2009.07.011>

547 Carvacho, O. F., Ashbaugh, L. L., Brown, M. S., & Flocchini, R. G. (2004).  
548 Measurement of PM2.5 emission potential from soil using the UC Davis



549 resuspension test chamber. *Geomorphology*, 59(1–4), 75–80.  
550 <https://doi.org/10.1016/j.geomorph.2003.09.007>

551 Colombo, C. & Miano, T. (2015) *Metodi di Analisi chimica del suolo*, 3rd edn. Società  
552 Italiana della Scienza del Suolo. Pubblicità & Stampa, Modugno (BA). (in  
553 Italian)

554 Denmead, O. T. (1983). Micrometeorological methods for measuring gaseous losses  
555 of nitrogen in the field. In J. R. Freney & J. R. Simpson (Eds.), *Gaseous Loss*  
556 *of Nitrogen from Plant-Soil Systems* (pp. 133–157). Dordrecht: Springer  
557 Netherlands. [https://doi.org/10.1007/978-94-017-1662-8\\_5](https://doi.org/10.1007/978-94-017-1662-8_5)

558 Dinuccio, E., Gioelli, F., Balsari, P., & Dorno, N. (2012). Ammonia losses from the  
559 storage and application of raw and chemo-mechanically separated slurry.  
560 *Agriculture, Ecosystems & Environment*, 153, 16–23.  
561 <https://doi.org/10.1016/j.agee.2012.02.015>

562 Dumortier, P., Aubinet, M., Lebeau, F., Naiken, A., & Heinesch, B. (2019). Point  
563 source emission estimation using eddy covariance: Validation using an  
564 artificial source experiment. *Agricultural and Forest Meteorology*, 266–267,  
565 148–156. <https://doi.org/10.1016/j.agrformet.2018.12.012>

566 EEA, European Environment Agency. (2016). *EMEP/EEA air pollutant emission*  
567 *inventory guidebook 2016: Technical guidance to prepare national emission*  
568 *inventories*. Retrieved from  
569 <http://bookshop.europa.eu/uri?target=EUB:NOTICE:THAL16020:EN>

570 Flesch, T. K., Wilson, J. D., Harper, L. A., Crenna, B. P., & Sharpe, R. R. (2004).  
571 Deducing Ground-to-Air Emissions from Observed Trace Gas Concentrations:  
572 A Field Trial. *Journal of Applied Meteorology*, 43(3), 487–502.  
573 [https://doi.org/10.1175/1520-0450\(2004\)043<0487:DGEFOT>2.0.CO;2](https://doi.org/10.1175/1520-0450(2004)043<0487:DGEFOT>2.0.CO;2)

- 574 Funk, R., Reuter, H. I., Hoffmann, C., Engel, W., & Öttl, D. (2008). Effect of moisture  
575 on fine dust emission from tillage operations on agricultural soils. *Earth*  
576 *Surface Processes and Landforms*, 33(12), 1851–1863.  
577 <https://doi.org/10.1002/esp.1737>
- 578 Fürmetz, A., Keppler, C., Knierim, U., Deerberg, F., & Heß, J. (2005). Laying hens in  
579 a mobile housing system-Use and condition of the free-range area. *Ende Der*  
580 *Nische, Beiträge Zur 8. Wissenschaftstagung Ökologischer Landbau*, 313–  
581 314.
- 582 Gao, S., Wang, Y., Shan, M., Teng, Y., Hong, N., Sun, Y., ... Zhang, H. (2020).  
583 Wind-tunnel and modelled PM10 emissions and dust concentrations from  
584 agriculture soils in Tianjin, northern China. *Aeolian Research*, 42, 100562.  
585 <https://doi.org/10.1016/j.aeolia.2019.100562>
- 586 Gebhardt-Henrich, S. G., Toscano, M. J., & Fröhlich, E. K. F. (2014). Use of outdoor  
587 ranges by laying hens in different sized flocks. *Applied Animal Behaviour*  
588 *Science*, 155, 74–81. <https://doi.org/10.1016/j.applanim.2014.03.010>
- 589 Hayes, E. T., Curran, T. P., & Dodd, V. A. (2006). Odour and ammonia emissions  
590 from intensive poultry units in Ireland. *Bioresource Technology*, 97(7), 933–  
591 939. <https://doi.org/10.1016/j.biortech.2005.04.024>
- 592 Hegelund, L., Sørensen, J. T., Kjaer, J. B., & Kristensen, I. S. (2005). Use of the  
593 range area in organic egg production systems: Effect of climatic factors, flock  
594 size, age and artificial cover. *British Poultry Science*, 46(1), 1–8.  
595 <https://doi.org/10.1080/00071660400023813>
- 596 Hirt, H., & Zeltner, E. (2000). Laying hen husbandry: Group size and use of henruns.  
597 *In: Alföldi, T., Lockeretz, W., Niggli, U. (Eds.), Proceedings 13th International*  
598 *IFOAM Scientific Conference*, 363.

599 Pope III, C. A.(2007). Mortality Effects of Longer Term Exposures to Fine Particulate  
600 Air Pollution: Review of Recent Epidemiological Evidence. *Inhalation*  
601 *Toxicology*, 19(sup1), 33–38. <https://doi.org/10.1080/08958370701492961>

602 Kabelitz, T., Ammon, C., Funk, R., Münch, S., Biniash, O., Nübel, U., ... Amon, T.  
603 (2020). Functional relationship of particulate matter (PM) emissions, animal  
604 species, and moisture content during manure application. *Environment*  
605 *International*, 143, 105577. <https://doi.org/10.1016/j.envint.2020.105577>

606 KNMI (2020). Royal Netherlands Meteorological Institute; data available at  
607 <https://www.knmi.nl/nederland-nu/klimatologie/uurgegevens>. Last access  
608 17/09/2020.Madden, N. M., Southard, R. J., & Mitchell, J. P. (2009). Soil  
609 Water Content and Soil Disaggregation by Disking Affects PM10 Emissions.  
610 *Journal of Environmental Quality*, 38(1), 36–43.  
611 <https://doi.org/10.2134/jeq2008.0209>

612 Madden, N. M., Southard, R. J., & Mitchell, J. P. (2010). Soil water and particle size  
613 distribution influence laboratory-generated PM10. *Atmospheric Environment*,  
614 44(6), 745–752. <https://doi.org/10.1016/j.atmosenv.2009.11.044>

615 Maffia, J., Dinuccio, E., Amon, B., & Balsari, P. (2020). PM emissions from open field  
616 crop management: Emission factors, assessment methods and mitigation  
617 measures – A review. *Atmospheric Environment*, 226, 117381.  
618 <https://doi.org/10.1016/j.atmosenv.2020.117381>

619 Menzi, H., Katz, P. E., Fahrni, M., Neftel, A., & Frick, R. (1998). A simple empirical  
620 model based on regression analysis to estimate ammonia emissions after  
621 manure application. *Atmospheric Environment*, 32(3), 301–307.  
622 [https://doi.org/10.1016/S1352-2310\(97\)00239-2](https://doi.org/10.1016/S1352-2310(97)00239-2)

623 MiPAF, Ministero per le Politiche Agricole e Forestali. (1997). Metodi di Analisi fisica  
624 del suolo. Società Italiana della Scienza del Suolo. Franco Angelo, Milano (in  
625 Italian)

626 Misselbrook, T. H., Nicholson, F. A., Chambers, B. J., & Johnson, R. A. (2005).  
627 Measuring ammonia emissions from land applied manure: An intercomparison  
628 of commonly used samplers and techniques. *Environmental Pollution*, 135(3),  
629 389–397. <https://doi.org/10.1016/j.envpol.2004.11.012>

630 Niekerk, T. G. C. M. van, Leenstra, F. R., Reuvekamp, B. F. J., Buissonjé, F. E. de,  
631 Aarnink, A. J. A., Ellen, H. H., & Koerkamp, P. W. G. G. (2016). *Inventarisatie*  
632 *van de effecten van uitloop pluimveehouderij op bodem-, water- en*  
633 *Luchtkwaliteit*. <https://doi.org/10.18174/385390>

634 Padoan, E., Maffia, J., Balsari, P., Ajmone-Marsan, F., & Dinuccio, E. (2021). Soil  
635 PM10 emission potential under specific mechanical stress and particles  
636 characteristics. *Science of The Total Environment*, 779, 146468.  
637 <https://doi.org/10.1016/j.scitotenv.2021.146468>

638 Pattey, E., & Qiu, G. (2012). Trends in primary particulate matter emissions from  
639 Canadian agriculture. *Journal of the Air & Waste Management Association*,  
640 62(7), 737–747. <https://doi.org/10.1080/10962247.2012.672058>

641 Pettersson, I. C., Freire, R., & Nicol, C. J. (2016). Factors affecting ranging behaviour  
642 in commercial free-range hens. *World's Poultry Science Journal*, 72(1), 137–  
643 150. <https://doi.org/10.1017/S0043933915002664>

644 R Core Team. (2019). R: A language and environment for statistical computing. R  
645 Foundation for Statistical Computing, Vienna, Austria. URL [https://www.R-](https://www.R-project.org/)  
646 [project.org/](https://www.R-project.org/).

647 R. W. Melse, P. Hofschreuder, & N. W. M. Ogink. (2012). Removal of Particulate  
648 Matter (PM10) by Air Scrubbers at Livestock Facilities: Results of an On-Farm

649 Monitoring Program. *Transactions of the ASABE*, 55(2), 689–698.  
650 <https://doi.org/10.13031/2013.41378>

651 Roumeliotis, T. S., & Van Heyst, B. J. (2008). Summary of Ammonia and Particulate  
652 Matter Emission Factors for Poultry Operations. *Journal of Applied Poultry  
653 Research*, 17(2), 305–314. <https://doi.org/10.3382/japr.2007-00073>

654 Stull, R. B. (2012). An introduction to boundary layer meteorology (Vol. 13). Springer  
655 Science & Business Media.van Liere, D. W., Kooijman, J., & Wiepkema, P. R.  
656 (1990). Dustbathing behaviour of laying hens as related to quality of  
657 dustbathing material. *Applied Animal Behaviour Science*, 26(1), 127–141.  
658 [https://doi.org/10.1016/0168-1591\(90\)90093-S](https://doi.org/10.1016/0168-1591(90)90093-S)

659 Vestergaard, K. S., Skadhauge, E., & Lawson, L. G. (1997). The Stress of Not Being  
660 Able to Perform Dustbathing in Laying Hens. *Physiology & Behavior*, 62(2),  
661 413–419. [https://doi.org/10.1016/S0031-9384\(97\)00041-3](https://doi.org/10.1016/S0031-9384(97)00041-3)

662 Winkel, A., van Riel, J. W., van Emous, R. A., Aarnink, A. J. A., Groot Koerkamp, P.  
663 W. G., & Ogink, N. W. M. (2016). Abatement of particulate matter emission  
664 from experimental aviary housings for laying hens by spraying rapeseed oil.  
665 *Poultry Science*, 95(12), 2836–2848. <https://doi.org/10.3382/ps/pew261>

666 Yao, Q., Yang, Z., Li, H., Buser, M. D., Wanjura, J. D., Downey, P. M., ... Hapeman,  
667 C. J. (2018). Assessment of particulate matter and ammonia emission  
668 concentrations and respective plume profiles from a commercial poultry  
669 house. *Environmental Pollution (Barking, Essex: 1987)*, 238, 10–16.  
670 <https://doi.org/10.1016/j.envpol.2018.02.039>

671 Zeltner, E., & Hirt, H. (2003). Effect of artificial structuring on the use of laying hen  
672 runs in a free-range system. *British Poultry Science*, 44(4), 533–537.  
673 <https://doi.org/10.1080/00071660310001616264>

674 Zeltner, Esther, & Hirt, H. (2008). Factors involved in the improvement of the use of  
675 hen runs. *Applied Animal Behaviour Science*, 114(3), 395–408.  
676 <https://doi.org/10.1016/j.applanim.2008.04.007>

677

678

679

680

681

682

683

684

685

686

687

688

689

690

691

692

693

694

695

696

697 **List of tables**

698 Table 1. Mean values and the 95% confidence intervals (CL) of ammonia emissions  
699 detected with the Impinger ( $I_{NH_3}$ ) and wind tunnel (S1, S2, S3) methodologies, at  
700 three different  $NH_3$  flow regulation levels (F1, F2 and F3). N = number of  
701 observations.

702

703

704

705

706

707

708

709

710

711

712

713

714

715

716

717

718

719

720

721

722

723

724

725

726

727

728

729

730

731 Table 1.

Sampling method	NH <sub>3</sub> regulation	N	NH <sub>3</sub> flux (mg) <sup>a</sup>	Lower CL	Upper CL
S3	F3	30	1672 a	1499	1844
I <sub>NH3</sub>			1559 a	1386	1731
S2			1492 ab	1319	1664
S1			1271 b	1099	1444
S3	F2	30	1106 a	933	1279
I <sub>NH3</sub>			993 a	820	1165
S2			926 ab	753	1098
S1			706 b	533	878
S3	F1	30	645 a	472	817
I <sub>NH3</sub>			532 a	359	704
S2			465 ab	292	637
S1			244 b	72	417

732 **a.** Means in column followed by a different letter differ significantly (P<0.05)

733



734 **List of figures**

735 Figure 1. Wind tunnel design (lateral and frontal view) and experimental layout for the  
736 wind tunnel validation test.

737

738 Figure 1. Ammonia flow assessment with impingers.

739

740 Figure 3. Scheme of Soil Resuspension Chamber (SRC) system.

741

742 Figure 4. Contouring of overgrazed are of outdoor run.

743

744 Figure 5. Average wind speed ( $\text{m s}^{-1}$ ) inside the tunnel as measured at 8 positions at  
745 0.2 m height inside the wind tunnel chamber.

746

747 Figure 6. Boxplot graphs representing the distribution of the measured ammonia  
748 concentrations ( $\text{mg kg}^{-1}$ ) in S1, S2 and S3.

749

750 Figure 7. Linear regression showing the relation between the logarithmic function of  
751  $\text{PM}_{10}$  ER ( $\text{mg m}^{-2} \text{hr}^{-1}$ ) and HD. The equation and  $R^2$  are shown in the graph.

752

753 Figure 8. Soil EP curves as influenced by moisture content (% on mass)

754

755 Figure 9. Estimated  $\text{PM}_{10}$  emission flux , rainfall and evapotranspiration (ET) fluxes,  
756 on a monthly basis.

757

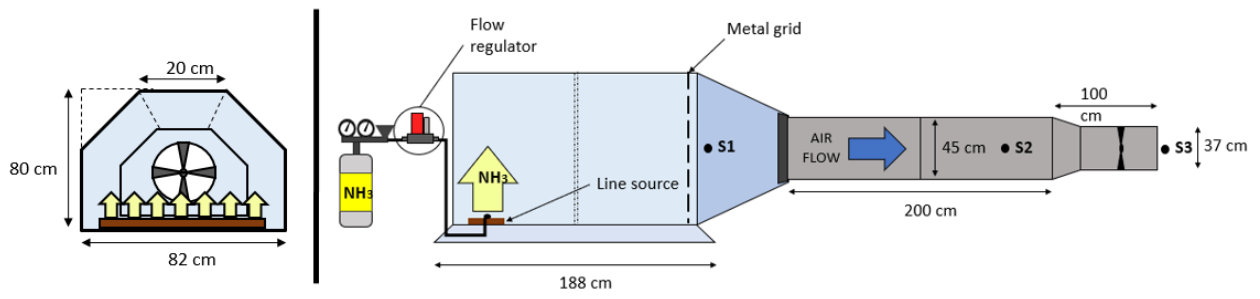
758

759

760

761

762 Figure 1.



763

764

765

766

767

768

769

770

771

772

773

774

775

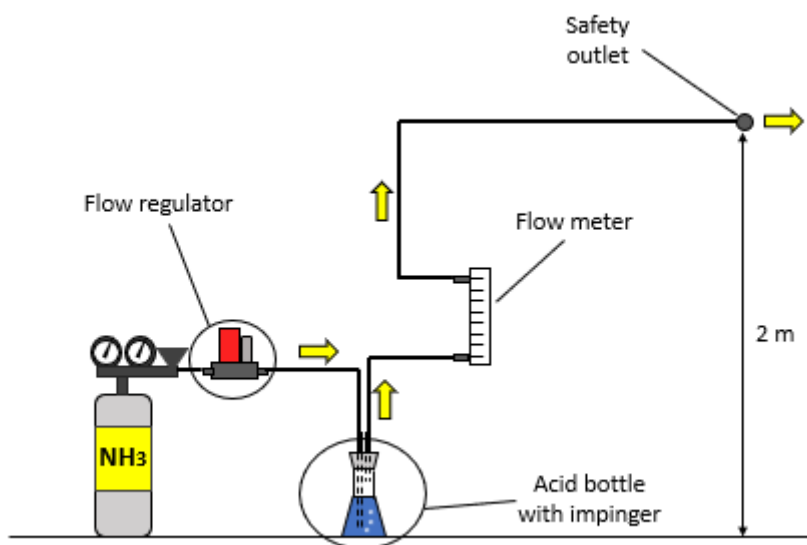
776

777

778

779

780 Figure 2.



781

782

783

784

785

786

787

788

789

790

791

792

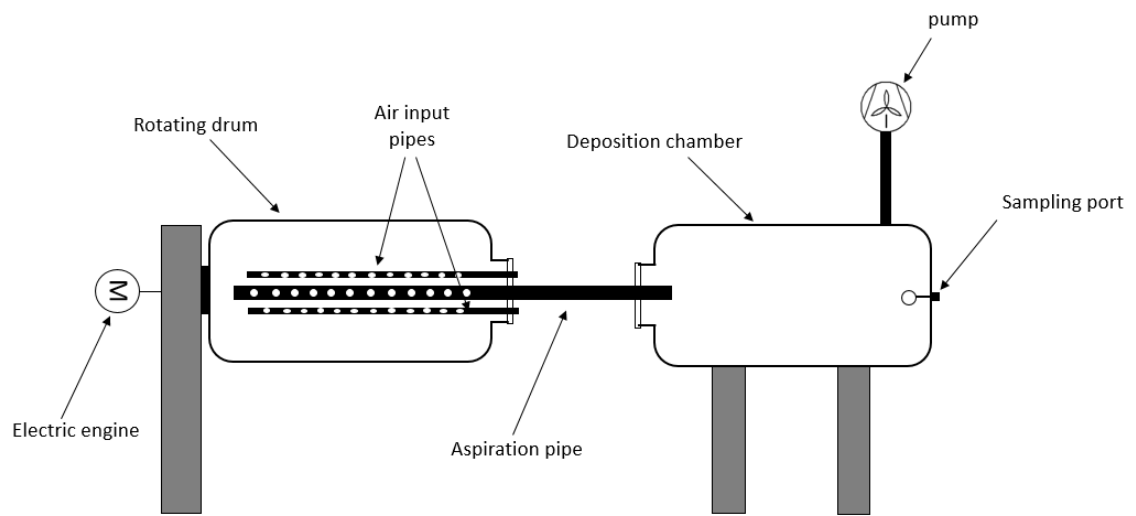
793

794

795

796

797 Figure 3.



798

799

800

801

802

803

804

805

806

807

808

809

810

811

812

813

814

815 Figure 4.



816

817

818

819

820

821 Figure 5.

Wind speed =  $1.5 \pm 0.11 \text{ m s}^{-1}$



1.0	1.5	1.4	1.4
2.3	2.0	1.7	1.6
0.9	1.4	1.3	1.2

822

823

824

825

826

827

828

829

830

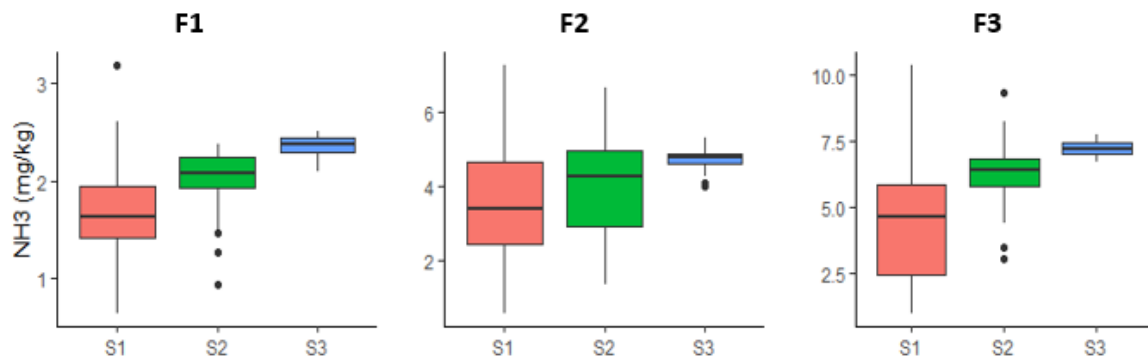
831

832

833

834

835 Figure 6.



836

837

838

839

840

841

842

843

844

845

846

847

848

849

850

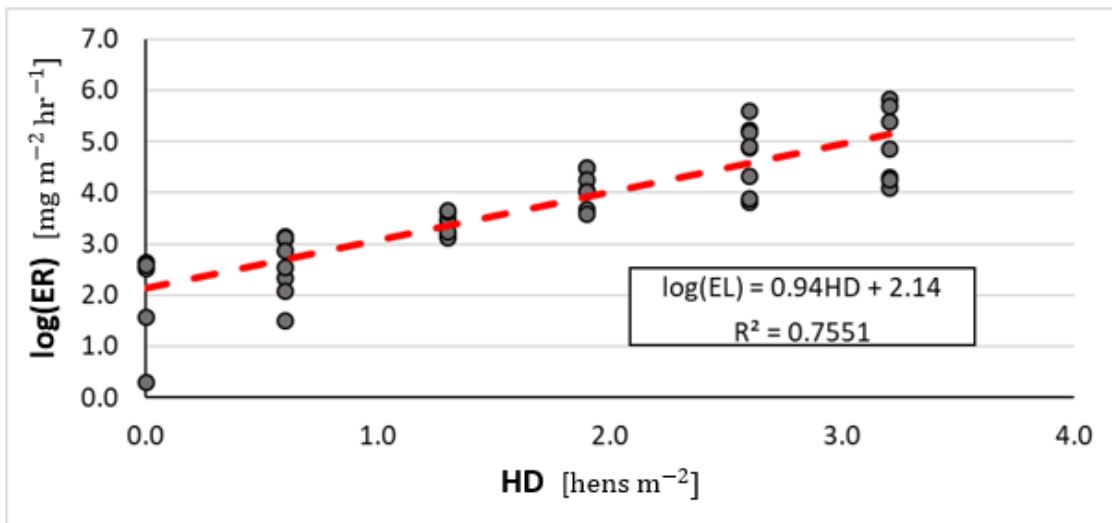
851

852

853

854 Figure 7.

855



856

857

858

859

860

861

862

863

864

865

866

867

868

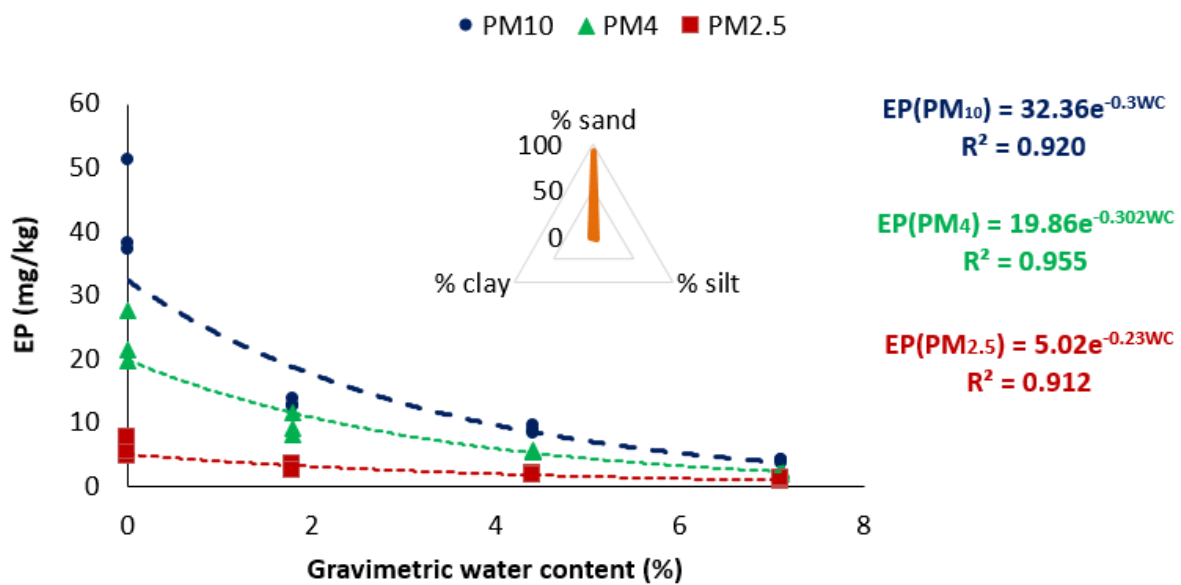
869

870

871



872 Figure 8.



873

874

875

876

877

878

879

880

881

882

883

884

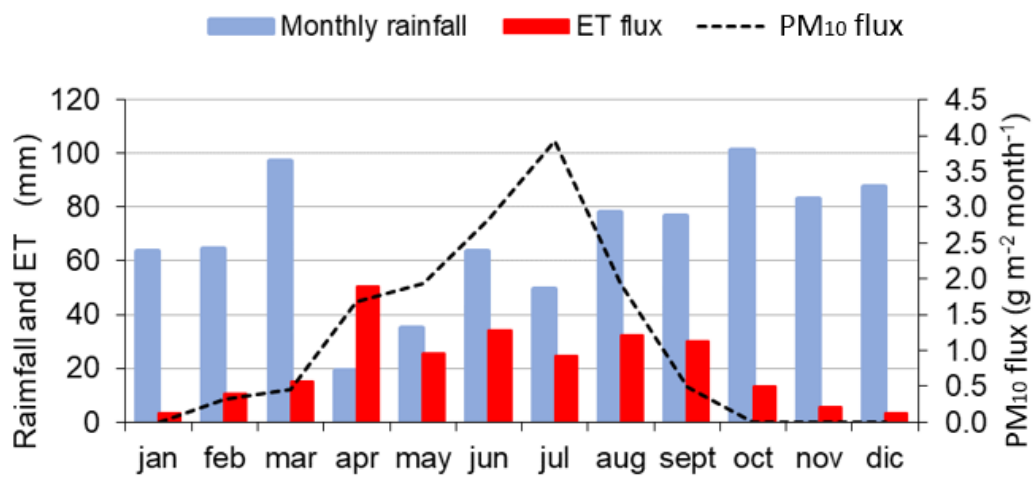
885

886

887

888

889 Figure 9.



890