



Title	Predicting atmospheric ammonia dispersion and potential ecological effects using monitored emission rates from an intensive laying hen facility in Ireland
Authors(s)	Kelleghan, David B., Hayes, Enda T., Everard, Mark, Curran, Thomas P.
Publication date	2021-02-15
Publication information	Kelleghan, David B., Enda T. Hayes, Mark Everard, and Thomas P. Curran. "Predicting Atmospheric Ammonia Dispersion and Potential Ecological Effects Using Monitored Emission Rates from an Intensive Laying Hen Facility in Ireland." Elsevier, February 15, 2021. https://doi.org/10.1016/j.atmosenv.2021.118214 .
Publisher	Elsevier
Item record/more information	http://hdl.handle.net/10197/12191
Publisher's version (DOI)	10.1016/j.atmosenv.2021.118214

Downloaded 2026-05-02 00:24:36

The UCD community has made this article openly available. Please share how this access benefits you. Your story matters! (@ucd_oa)



© Some rights reserved. For more information

1 **Title: Predicting atmospheric ammonia dispersion and potential ecological effects using**
2 **monitored emission rates from an intensive laying hen facility in Ireland.**

3 **Authors:** David B. Kelleghan^a, Enda Hayes^b, Mark Everard^c, Thomas P. Curran^a

4 ^a*UCD School of Biosystems and Food Engineering, University College Dublin, Belfield, Dublin 4,*
5 *Ireland.*

6 ^b*Air Quality Management Resource Centre, University of the West of England, Frenchay*
7 *Campus, Coldharbour Lane, Bristol BS16 1QY, UK*

8 ^c*International Water Security Network, University of the West of England, Frenchay Campus,*
9 *Coldharbour Lane, Bristol BS16 1QY, UK*

10 **Corresponding Author:** david.kelleghan@ucd.ie

11

12 **Predicting atmospheric ammonia dispersion and potential ecological effects using monitored**
13 **emission rates from an intensive laying hen facility in Ireland.**

14 **Abstract**

15 Agriculture is responsible for 98% of atmospheric ammonia (NH₃) in Ireland, of which pigs and
16 poultry produce 7%;with laying hens specifically contributing 0.6%. Though a small proportion
17 of the national NH₃ total emissions, the ecological impacts on sensitive sites attributed to laying
18 hen farms can be substantial. NH₃ emission monitoring was conducted in Spring (February to
19 March) and Summer (July to August) 2016 to account for seasonal variation. The total average
20 emission and ventilation rate was 0.25 g bird⁻¹ day⁻¹ and 931 cm³ s⁻¹ bird⁻¹. This is lower than the
21 previously used emission factor for the Irish national inventory of 0.5 g bird⁻¹ day⁻¹, but broadly
22 similar to factors reported in the United Kingdom (UK) and the European Union (EU). Dispersion
23 modelling using monitored data indicated potentially acute effects within 84 m, critical level
24 exceedance within 312 m and exceedance of 0.3 kg N ha⁻¹ year⁻¹ deposition within 2.9 – 5.2 km.
25 The sensitivity of the model was tested using SCAIL-Agriculture emission and ventilation rates
26 which showed P-values for one tailed critical level below 0.01 for all models, indicating that
27 when normalised the maximum extents modelled by AERMOD were significantly different. This
28 analysis showed emission rate having more influence than ventilation rate. Both parameters
29 combined had the greatest increase in dispersion extent, on average 55.8 % greater than the
30 use of monitored rates. A deposition rate of 0.3 kg N ha⁻¹ year⁻¹ was reached within 5.1 – 7.7 km
31 when using SCAIL-Agriculture rates, indicating that the use of SCAIL-Agriculture recommended
32 emission and ventilation rates would have been sufficiently precautionary to assess negative
33 ecological effects on a Natura 2000 site under the Habitats Directive (92/43/EEC). In relation to
34 Appropriate Assessment (AA) screening, the use of any contribution from a source within a set
35 distance may be an appropriate full AA trigger.

36 **1. Introduction**

37 Egg production in the Republic of Ireland accounts for €49 million of agricultural output per
38 annum, with c. 250 producers employing 800 people (Department of Agriculture Food and the
39 Marine, 2015). Approximately 45,000 tonnes of eggs are produced annually (Food and
40 Agriculture Organization, 2014). In 2015, Ireland reported a total of 67,000 kg of ammonia (NH₃)
41 emissions from laying hens, accounting for 0.6% of Ireland's total (European Environment
42 Agency, 2017). Due to the production of eggs typically in intensive laying hen farms, they are
43 associated with higher local concentrations of NH₃ (Tang et al., 2018) contributing to ecological
44 impacts (Sutton et al., 2011, Sutton, 2007). On the other hand, the majority of ammonia
45 emissions (91%) is generated from more diffuse sources such as cattle, slurry spreading and
46 synthetic fertilisers (European Environment Agency, 2017). As these are diffuse sources, there
47 is a lower risk for high ammonia concentrations; though their contribution to impacts should not
48 be discounted. In line with the Industrial Emissions Directive (2010/75/EU) (European Union,
49 2010), European BAT (Best Available Technology) reference documents recommend a number
50 of systems in which laying hens should be housed. These include aviaries, deep litter with a
51 manure pit, and enriched cage systems. Guidance recommends a number of practices to reduce
52 emissions for each housing system (European Commission, 2013). In the case of aviaries and
53 cage systems, these recommendations include removal of manure either weekly with additional
54 drying or bi-weekly with no drying. A number of approaches are recommended for deep litter
55 systems, which generally have much higher emission rates than caged or aviary systems (Hayes
56 et al., 2006; Starmans and Van Der Hoek, 2007; Hill et al., 2014); including forced air drying of
57 manure, enhanced ventilation, air blowing from below via a perforated floor, etc. (European
58 Commission, 2017). Battery production systems have been banned in the European Union since
59 the Council Directive (1999/74/EC) on the protection of laying hens (European Commission, 1999).

60 The ventilation rate plays an integral role in housed poultry management, where it influences
61 both the welfare of the birds indoors (Wathes et al., 1983), and the NH₃ emission rate (Alberdi
62 et al., 2016) in addition to the extent of the NH₃ dispersion plume from the house. Estimation of
63 ventilation rates using Carbon Dioxide (CO₂) mass balance is a longstanding practice both in
64 Europe and America (Seedorf et al., 1998; Li et al., 2005; Mosquera et al., 2012; Hill et al., 2014).
65 This method requires a series of equations calculating the animal activity, total heat and CO₂
66 production to estimate the ventilation rate of a livestock building. These equations have been
67 derived from work produced by the International Commission of Agricultural Engineering
68 (Pedersen & Sällvik, 2002).

69 The United Nations Economic Commission for Europe (UNECE) has set “critical levels” for
70 atmospheric ammonia, which are atmospheric concentrations above which adverse ecological
71 effects can be expected - these are set at 1 µg NH₃ m⁻³ for lichens and moss species and 3 µg NH₃
72 m⁻³ for higher plants (United Nations Economic Commission For Europe, 2007). Critical loads
73 require the calculation of deposition velocities, where a critical level acts as a useful tool which
74 can directly indicate potential impacts without further calculation or estimation. Recent work
75 has shown that internationally applied empirical critical loads for nitrogen may be too high to
76 represent impacts in Ireland, which occur at lower deposition rates. Wilkins et. al. (2016)
77 identified species change points in Ireland within a range of 3.9 to 15.3 kg N ha⁻¹ yr⁻¹ compared
78 to imperial critical loads of 5 to 30 kg N ha⁻¹ yr⁻¹. For example, species change points of 4.9 and
79 4.1 kg N ha⁻¹ yr⁻¹ were observed for Northern Atlantic wet heaths with *Erica tetralix* [Annex I
80 Habitat Code 4010] and European dry heaths [Annex I Habitat Code 4030], respectively, which
81 are both significantly lower than previously used empirical critical load ranges of 10–15 and 10–
82 20 kg N ha⁻¹ yr⁻¹ (Bobbink & Hettelingh, 2011).

83 A common purpose of the EU Habitats Directive (92/43/EEC) (European Economic Committee,
84 1992) and EU Birds Directive (2009/147/EC) (European Commission, 2009) is to preserve and

85 maintain favorable conservation status on designated sensitive sites across Europe, comprising
86 the Natura 2000 network. The Habitats Directive (92/43/EEC) (European Economic Committee,
87 1992) introduced a tiered approach to environmental assessments specific to Natura 2000 sites
88 under Article 6 (3) of this Directive, stating that "...any plan or project not directly connected
89 with or necessary to the management of the site but likely to have a significant effect thereon,
90 either individually or in combination with other plans or projects, shall be subject to appropriate
91 assessment of its implications for the site in view of the site's conservation objectives". This
92 assessment process takes a tiered approach, where stage one is intended to screen out any
93 potential significant effects. If, after stage one, potential negative effects have not been ruled
94 out, or there is remaining uncertainty, the assessment process must move to stage two for a full
95 Appropriate Assessment (AA). Different Member States have quantified the potential for
96 significant ecological effects arising from atmospheric NH₃ differently. The UK, for example, uses
97 a 1% exceedance of critical levels and loads as an indicator of significance (Hicks et al., 2011),
98 and the Dutch approach considers any contribution, even less than 0.001 kg N ha⁻¹ year⁻¹ (0.02%
99 of 5 kg N ha⁻¹ year⁻¹), to require a detailed assessment. The Dutch Nitrogen Case (C 293/17 & C
100 294/17)(CJEU, 2019) however found the Dutch approach was non-compliant with the Habitats
101 Directive (92/43/EEC) (European Economic Committee, 1992) as any contribution to a Natura
102 2000 site already impacted could be constituted as a significant negative effect thereon (Anker
103 et al., 2019). While the level of significance is likely to vary between countries, as a combination
104 of internal government policies and ambient concentrations nationally, previous European
105 guidance states only contributions of 0.3 kg N ha⁻¹ year⁻¹ or above need to be considered for full
106 appropriate assessment (IMPEL, 2017). This rate of 0.3 kg N ha⁻¹ year⁻¹ is based on the approach
107 in Germany, which may also be non-compliant with the Habitats Directive (92/43/EEC)
108 (European Economic Committee, 1992) following the Dutch Nitrogen Case. Current guidance
109 from the outcomes of the Dutch Nitrogen Case (C 293/17 & C 294/17)(CJEU, 2019) implies any

110 contribution of additional NH₃ or nitrogen to a Natura 2000 may require a full AA (Anker et al.,
111 2019).

112 The SCAIL-Agriculture tool, which was developed for use in the UK and adapted for Ireland,
113 utilizes AERMOD, a dispersion model developed by the United States EPA, to screen potential
114 contributions of atmospheric NH₃ to Natura 2000 sites (Hill et al., 2014). Though AERMOD was
115 initially developed to model dispersion from industrial stacks, it has been employed in a number
116 of studies researching atmospheric dispersion of pollutants from poultry houses (Hadlocon et
117 al, 2015; Huang & Guo, 2019; Baker et al., 2020). The potential for negative ecological effects on
118 Natura 2000 sites from atmospheric NH₃ is substantial, not just from contributions from hotspot
119 sources such as laying hen farms. In Ireland, 80% of these sites are estimated to exceed the
120 lower critical level of 1 µg m⁻³, and 6.9% to exceed the critical level for higher plants at 3 µg m⁻³
121 (Kelleghan et al., 2020). Contributions from hotspot sources are likely to be much higher, for
122 example contributions of up to 34 µg m⁻³ was monitored on Moninea Bog as a result of a laying
123 hen facility (Sutton, 2007; Sutton et al., 2011). This site was downwind of an intensive laying hen
124 farm in operation since the early 1990s, which had upgraded to incorporate manure removal by
125 conveyor belt and drying in 2005 (Sutton, 2007). On a number of trees downwind of this laying
126 hen house, epiphytic lichens had been replaced with a thick algal slime indicative of severe
127 eutrophication with NH₃ concentrations of 8 µg m⁻³. Sutton et al. (2011) estimated that more
128 than 90% of *Cladonia* and *Sphagnum* species were eradicated or degraded within 200 m
129 downwind of the farm. This site is typical of a bog with acute impacts from atmospheric NH₃ due
130 to high contributions from the neighboring laying hen farm. Since the closure of this farm, the
131 site has begun to slowly recover from these effects though the precise rate of recovery is not
132 yet fully understood (van Dijk, 2019).

133 The objectives of this study were to:

- 134 • Monitor the NH₃ emission and ventilation rates for a modern layer house with manure
135 drying, weekly removal and mechanical ventilation.
- 136 • Model dispersion of NH₃ into the atmosphere using AERMOD to gauge the layer
137 building's contribution to local ecological impacts.
- 138 • Assess the sensitivity of the model using rates recommended by SCAIL-Agriculture,
139 testing the effect of recommended and monitored emission and ventilation rates on
140 modelled dispersion extents and severity of impacts.
- 141 • Review the suitability of a presumed *de minimis* deposition rate of 0.3 kg N ha⁻¹ year⁻¹
142 and percent thresholds for stage 1 AA screening under the Habitats Directive
143 (92/43/EEC) (European Economic Committee, 1992).

144 **2. Methods**

145 **2.1. Farm description**

146 An intensive laying hen farm in Ireland exposed to a temperate oceanic climate was monitored
147 as part of this study. This farm utilised three operational laying hen houses, where they were
148 housed for a 56 – 60 week laying cycle and are generally removed when 72 – 76 weeks old. This
149 farm uses enriched cage houses. All three houses are of identical size and layout, covering 78 x
150 16 m and standing 7.7 m tall. Each house has the capacity for c. 42,000 laying hens. Water is
151 supplied ad-lib through button nipple drinking system, minimising leakages. All laying hen
152 houses on site are mechanically ventilated, controlled by temperature and humidity. Due to the
153 combination of ventilation type, heat produced by laying hens and insulation, no additional
154 heating is required for laying hen houses on site. During ammonia emission monitoring, the
155 bird's diet contained a 16% protein content.

156 The resulting litter from the production process, comprising entirely bird droppings, is dried
157 prior to removal on the conveyor belt using recirculated air. The farm is estimated to produce
158 3,688 m³ of manure per year, which is sold as an organic fertiliser. Manure is removed weekly

159 via conveyor belt and is stored in a naturally ventilated manure storage facility located on the
160 north end of the site directly adjacent laying hen houses. The manure storage facility was not
161 monitored or modelled as part of this project. Though manure storage is likely to contribute to
162 local NH₃ concentrations, this is expected to be minimal as manure in storage was dried and
163 covered from rain.

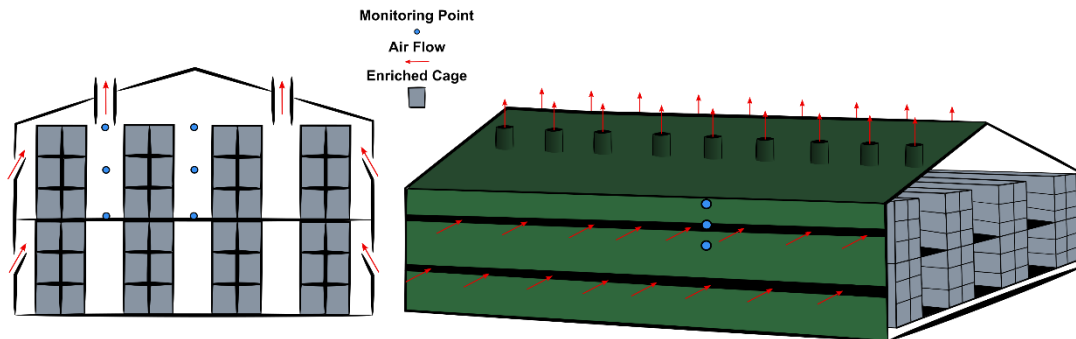
164 **2.2. Monitoring**

165 The Los Gatos Research Ultraportable Ammonia Analyser (UAA) was used to monitor indoor
166 concentrations of atmospheric ammonia. The UAA was tested in laboratory conditions and
167 accurately measured known concentrations of 25 ppm, which is within its operational range of
168 0 – 200 ppm. The UAA was evaluated against a number of other similar NH₃ sensors during field
169 trials in Edinburgh, UK supervised by the Centre for Ecology and Hydrology (Twigg et al., 2018),
170 where it showed the lowest relative deviation from the mean than a number of other advanced
171 sensors. An older model, the Los Gatos Research “Ammonia Analyser – Trace” has been used by
172 Ricardo-AEA in the UK to monitor concentrations of NH₃ inside UK poultry houses (Leonard,
173 2014, pers. comm.).

174 An eight-inlet multipoint unit was used to allow for sampling of six locations inside the house, in
175 addition to a single sample location outside. Indoor CO₂ concentrations were monitored using a
176 K30 CO₂ sensor (Senseair, Sweden), which has a measurement range of 0 – 10,000 ppm with an
177 accuracy of ± 3% of measured value. This sampled the outflow of the UAA which allowed for
178 monitoring of CO₂ and NH₃ in the same locations inside the laying hen house. Outdoor CO₂
179 measurements for the monitoring period were obtained from Ireland’s only ambient CO₂
180 monitoring station on Mace Head.

181 The six indoor sample locations were divided into two sets of three, each within an aisle between
182 cages. The sample inlets were placed above the bottom three cages, aligned with the fifth cage
183 and above the sixth cage below exhaust fan (Figure 1). All records obtained from the UAA and

184 K30 sensors were averaged per minute. Temperature was monitored indoors using an Elitech
185 temperature data logger.



186

187 Figure 1. Monitoring layout.

188 Monitoring was conducted over 67 days covering two stages of the year in order to account for
189 seasonal variability; monitoring ran over the Spring months (14/02/2016 – 20/03/2016) and
190 Summer months (20/07/2016 – 20/08/2016). Temperatures were typical of monthly averages
191 from 2014 – 2017.

192 2.3. Data management

193 A record was produced every second for indoor NH_3 concentration, and every two seconds for
194 CO_2 concentration in the same location with each sampling point recorded in sequence. Every
195 sampling location was monitored for 40 minutes, which was followed by 20 minutes of outdoor
196 monitoring in order to regularly flush the UAA. Outdoor monitoring was excluded from data
197 analysis, but provided reliable breaks in monitoring data where concentrations decreased to
198 outdoor levels between indoor sampling periods.

199 The data representative of both increasing and decreasing concentrations shown in Figure 2 was
200 removed, leaving only the concentration plateau, which was averaged for each minute and
201 coupled with the corresponding CO_2 measurements in Microsoft Excel. These measurements
202 were averaged per minute.

203 **2.4. Calculating ventilation & emission rate**

204 CO₂ mass balance was used to calculate the ventilation rate of the building for every averaged
205 minute record. This required the use of a series of equations, based on animal activity, heat
206 production and CO₂ production (Pedersen & Sällvik, 2002). This produced a semi-continuous
207 emission rate for each sample location inside the laying hen house. Box and Whisker plots for
208 the monitored emission rates for the house monitored were generated using the R statistical
209 programme (R Core Team, 2013). These Box and Whisker plots were used to analyse the
210 relationship of emissions with season, month, day of week, and hour of day. As monitoring took
211 place in both warm and cold seasons, the overall average produced was intended to account for
212 this variability.

213 **2.5. Modelling atmospheric dispersion and deposition of ammonia**

214 Local meteorological data (2016) was obtained from the closest synoptic Met Éireann station,
215 which was 35 km from this farm. As this study focuses on testing the effect of monitored
216 ventilation and emission rates on dispersion modelling, the use of any continuously monitored
217 meteorological data would have been appropriate, regardless of proximity to layer house. Lakes
218 Environmental © AERMOD v. 9.6 was used to model the dispersion of atmospheric NH₃ using
219 the average rates observed for the monitoring period. Modelling was conducted to compare
220 four scenarios based on differing emission and ventilation rates; 1. Monitored Emissions &
221 Monitored Ventilation rates (MEMV), 2. Monitored Emissions & SCAIL Ventilation (MESV), 3.
222 SCAIL Emissions & Monitored Ventilation (SEMV), 4. SCAIL Emissions & SCAIL Ventilation (SESV).

223

224 **Table 1. List of data required and sources for running atmospheric dispersion modelling in**
 225 **AERMOD 9.6.**

Data	Source
Meteorological data	Met Éireann Dunsany Meteorological Station (2016)
Topographical data	Shuttle Radar Topography Mission 1/3 – 30 m resolution
SCAIL-Agriculture Emission Factors & Ventilation Rates	Hill et al. (2014)
Monitored Emission Rates	Average of monitoring conducted by this study
Ventilation Rates	Average of monitoring conducted by this study
Source Height	7.7 m – Local authority planning application
Gas Exit Temperature	24.3°C – Monitored Average
Effective Diameter	4.24 m - Measured on site and with satellite imagery

226

227 As both monitoring and modelling conducted estimates a ventilation rate for the building and
 228 not for each exhaust independently, a total effective diameter was calculated for the building
 229 (Hill et al., 2014). This summed the area of all fans, and then calculated the diameter presuming
 230 a single outlet, as below;

231
$$total\ fan\ area = (\pi \times fan\ radius^2) \times no.\ of\ fans$$

232
$$effective\ diameter = (\sqrt{(total\ fan\ area/\pi)}) \times 2$$

233 This was applied to the equation below in order to calculate the exit velocity of air from the
 234 building;

235
$$\frac{flow\ rate}{\pi \times effective\ radius^2}$$

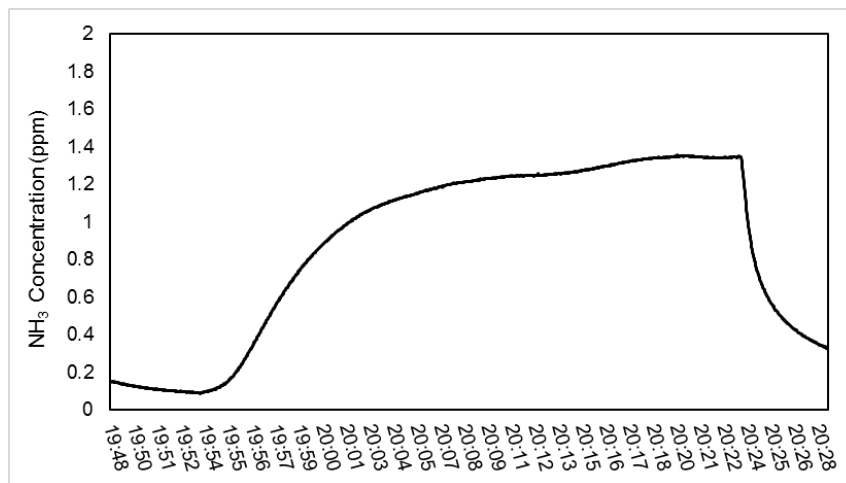
236 Contours from AERMOD modelling were set to best reflect potential negative ecological effects.
 237 These were set to indicate potential severe effects (8 and 5 $\mu\text{g m}^{-3}$), critical level exceedance (3
 238 and 1 $\mu\text{g m}^{-3}$), presumed *de minimis* deposition values (0.06 and 0.04 $\mu\text{g m}^{-3}$), and percent
 239 threshold exceedance values (0.12, 0.04, 0.03 and 0.01 $\mu\text{g m}^{-3}$). These percent threshold values
 240 are those recommended by Hicks et al. (2011) for 1 – 4 % of critical levels, which in practice are

241 also intended to be applied to critical load exceedances. Dry deposition of NH_3 was modelled in
242 Excel, presuming deposition velocities as presented in the SCAIL-Agriculture report for woodland
243 (3 cm s^{-1}) and other surfaces (2 cm s^{-1}) (Hill et al., 2014).

244 3. Results

245 3.1. Concentration monitoring example

246 Monitoring at all locations was carried out in sequence, with each point being monitored for 40
247 minutes as shown in Figure 2. Figure 2 is an example highlighting an initial increase in monitored
248 concentration as the sample was transported from the location inside the house to the sensor
249 stored outdoors through PTFE tubing, a concentration plateau representative of the actual
250 indoor concentration and an eventual decline as monitoring outdoors began. The plateau was
251 used to represent monitored concentration at that location.



252

253 **Figure 2. Example of Indoor NH_3 concentration trend during one monitoring period.**

254 3.2. Emission Monitoring

255 The average daily NH_3 emission rates from the monitored laying hen house are shown in Table
256 2. As the Irish EPA currently report emission factors in $\text{g bird}^{-1} \text{ day}^{-1}$, this was used throughout
257 this paper. Emission rates are also presented in $\text{kg bird}^{-1} \text{ year}^{-1}$, $\text{g day}^{-1} \text{ kg}^{-1}$ and $\text{g day}^{-1} \text{ LU}^{-1}$
258 (Livestock Unit, i.e. 500 kg) in Table 2. The average NH_3 emission rate for the full 63-day
259 monitoring day period is $0.25 \text{ g bird}^{-1} \text{ day}^{-1}$, which is composed of cold and warm season emission
260 rates of 0.20 and $0.29 \text{ g bird}^{-1} \text{ day}^{-1}$, respectively. Further dividing seasonal emissions into the
261 months during which monitoring took place, sees the lowest emission rate in February of 0.16 g

262 bird⁻¹ day⁻¹ increasing to 0.23 g bird⁻¹ day⁻¹ in March. The highest rate occurred in July, with a rate
 263 of 0.33 g bird⁻¹ day⁻¹ reducing to 0.27 g bird⁻¹ day⁻¹ in August. These rates correspond with
 264 average temperature for these periods, also listed in Table 2. Lower emission rates, ventilation
 265 rates and exit velocities occur during cold weather. Table 2 also details average emissions based
 266 on the day of the week, where emissions are highest at 0.35 g bird⁻¹ day⁻¹ on Sunday, reducing
 267 to 0.11 g bird⁻¹ day⁻¹ on Wednesday. The ventilation rate observed during monitoring was 38.55
 268 m³ s⁻¹, equivalent to 931.16 cm³ s⁻¹bird⁻¹.

269 **Table 2. Averaged ventilation rates, exit velocities and emission rates over different periods.**

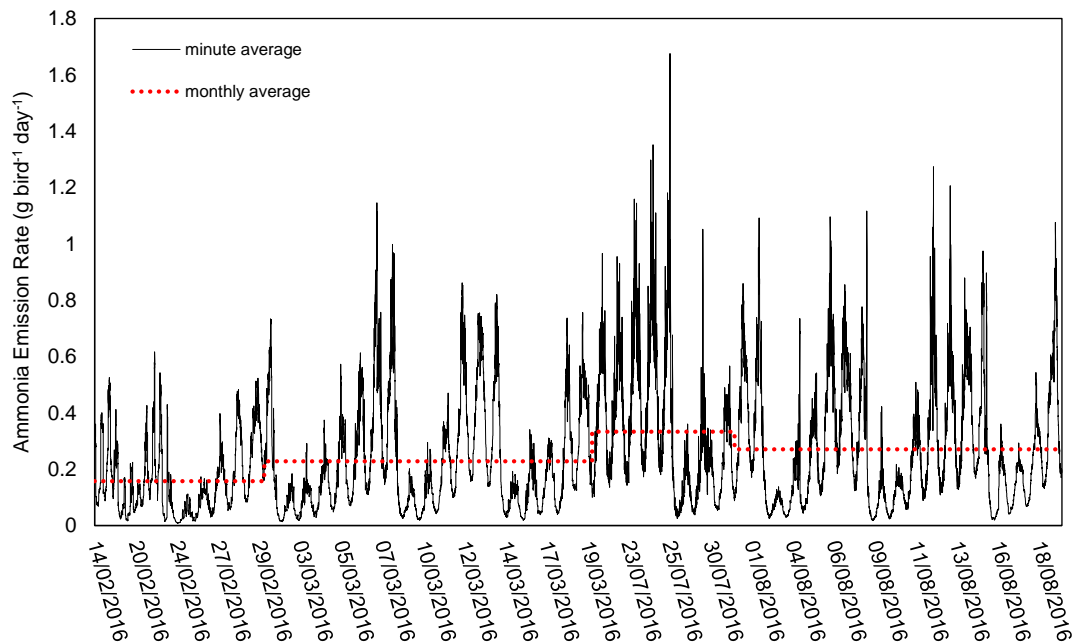
270 **Representative SCAIL-Agriculture ventilation & emission rates included.**

Averaging Period	Outside Temperature (°C)	Ventilation Rate (m ³ s ⁻¹)	Ventilation Rate (cm ³ s ⁻¹ bird ⁻¹)	Exit Velocity (m s ⁻¹)	NH ₃ (g bird ⁻¹ day ⁻¹)	NH ₃ (kg bird ⁻¹ year ⁻¹)	NH ₃ (g day ⁻¹ kg ⁻¹)	NH ₃ (g day ⁻¹ LU ⁻¹)
AmmoniaN2K	9.99	38.55	931.16	2.73	0.25	0.09	0.13	64.60
SCAIL	9.99	28.57	690.1	2.02	0.33	0.12	0.17	86.52
Cold	4.94	26.55	641.3	1.88	0.20	0.07	0.11	53.61
Warm	15.34	51.24	1237.68	3.63	0.29	0.11	0.15	76.23
February	3.67	21.21	512.32	1.50	0.16	0.06	0.08	41.35
March	5.60	29.31	707.97	2.08	0.23	0.08	0.12	59.96
July	15.46	56.80	1371.98	4.02	0.33	0.12	0.18	87.72
August	15.29	48.83	1179.47	3.46	0.27	0.10	0.14	71.23
Monday	9.43	38.21	922.95	2.71	0.34	0.12	0.18	89.03
Tuesday	10.98	41.38	999.52	2.93	0.20	0.07	0.11	52.97
Wednesday	9.34	35.79	864.49	2.53	0.11	0.04	0.06	28.74
Thursday	9.57	38.88	939.13	2.75	0.16	0.06	0.09	43.34
Friday	10.04	37.51	906.04	2.66	0.25	0.09	0.13	66.93
Saturday	10.41	41.16	994.2	2.91	0.31	0.11	0.16	82.45
Sunday	10.22	36.90	891.3	2.61	0.35	0.13	0.18	91.07

271

272

273 Figure 3 below shows real time NH₃ emissions based on minute averages collected during the
274 monitoring period. Diurnal, weekly and seasonal variation in emissions are apparent within this
275 graph. These trends are further analysed in the Box and Whisker Plots in Figure 4. Detailed rates
276 presented are overlaid by the respective monthly average emission rate, highlighting the high
277 peaks that occur beyond this average throughout the week.



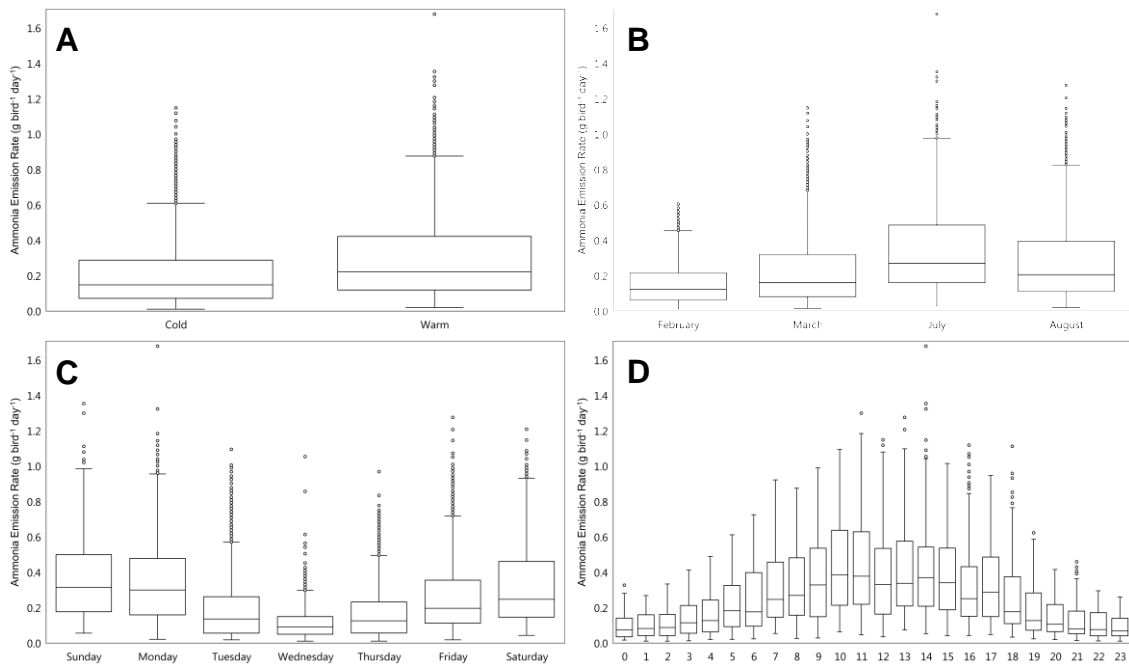
278

279 **Figure 3. Emissions from laying hen house during two seasons.**

280 Box and Whisker Plots were generated to display the variation of emission rates during the
281 monitoring period. Figure 4.A. shows the Box and Whisker Plot for emissions during spring and
282 summer months. Where the median and upper extremes are lower for the cold period
283 compared to warm. The same pattern is observed for both the upper and lower quartiles. Figure
284 4.B. clearly shows much lower emission rates in February compared to other months. The upper
285 whisker for March emissions increases from February with increased temperatures. Both July
286 and August show similar median emission rates, though August's upper extreme is less than
287 July's. Figure 4.C. shows the weekly emissions from the laying hen house, where a clear trend in
288 median emission rates is observed increasing from Wednesday to Monday and decreasing
289 following manure removal on Tuesday. Emissions occurring on Wednesdays also exhibit a lower

290 diversity of emission rates with tighter upper and lower extremes. Hourly variation of emissions
291 is presented in Figure 4.D. where peaks occur just prior to and following mid-day at 11:00 and
292 13:00, with lowest emissions occurring at midnight.

293



294

295 **Figure 4. Box and Whisker Plots of averaged NH₃ emission rates from laying hen house per**
296 **season (A), per month (B), per day of week (C) and per hour (D).**

297 3.3. Concentration & dry deposition modelling

298 Atmospheric dispersion modelling conducted using Lakes © AERMOD, compared the maximum
299 dispersion extent of models created using monitored and guidance rates from SCAL-Agriculture
300 (Hill et al., 2014). Average rates for “AmmoniaN2K” (Overall average monitored rates) and
301 “SCAL” (Recommended figures from SCAL-Agriculture guidance) from Table 2 were used to
302 generate models. Table 3 details the maximum extent downwind to which contours were
303 modelled for four scenarios, based on combinations of monitored and recommended ventilation
304 and emission rates to apply to dispersion models in practice. The four modelled scenarios
305 included the following combinations;

- 306 • Monitored Emission and Monitored Ventilation (MEMV)
- 307 • Monitored Emission and SCAIL-Agriculture Ventilation (MESV)
- 308 • SCAIL-Agriculture Emission and Monitored Ventilation (SEMV)
- 309 • SCAIL-Agriculture emission and SCAIL-Agriculture Ventilation (SESV)

310 Table 3 summarises the maximum distance downwind modelled concentrations occurred from
311 four scenarios listed. These predicted concentration and deposition rates do not include
312 background concentrations of NH₃ or deposition of nitrogen. Modelled contributions from the
313 farm alone exceeded the lower critical level of 1 µg m⁻³ within 312, 367, 400 and 468 m for
314 MEMV, MESV, SEMV and SESV respectively. While the higher critical level of 3 µg m⁻³ is exceeded
315 from the housing alone within 118, 150, 160 and 194 m for MEMV, MESV, SEMV and SESV. These
316 critical level exceedances are highlighted by the modelled contours presented in Appendix 1. A
317 concentration of 5 µg m⁻³ is exceeded within 84, 106, 106 and 122 m for MEMV, MESV, SEMV
318 and SESV.

319

320

321 **Table Error! No text of specified style in document.. Maximum distance downwind of farm**
 322 **where concentrations of NH₃ are modelled for 2016, comparing AERMOD dispersion model**
 323 **outputs generated using monitored, EPA and SCAIL-Agriculture emission rates.**

NH ₃ Concentration (µg m ⁻³)	Dry Deposition (kg N ha ⁻¹ yr ⁻¹)		Farthest Distance (m)			
	Other	Woodland	Monitored Emissions & Ventilation (MEMV)	Monitored Emissions & SCAIL Ventilation (MESV)	SCAIL Emissions & Monitored Ventilation (SEMV)	SCAIL Emissions & Ventilation (SESV)
0.01	0.05	0.08	27419	27644	30312	32002
0.03	0.16	0.23	6808	7681	9361	9659
0.04	0.2	0.3	5227	5259	7504	7705
0.06	0.3	0.5	2980	3370	4825	5104
0.12	0.6	0.9	1675	1923	2722	2857
1	5.2	7.8	312	367	400	468
3	15.6	23.4	118	150	160	194
5	25.9	39	84	106	106	122
8	41.6	62.3	0	71	68	95

324 The *de minimis* value for dry deposition of nitrogen from a hotspot agricultural source was set
 325 at 0.3 kg N ha⁻¹ year⁻¹ by the European Union Network for the Implementation and Enforcement
 326 of Environmental Law (IMPEL) (IMPEL, 2017). Modelled scenarios for dry deposition across low
 327 vegetation (i.e. grasslands and bogs) indicate this rate is achieved within 2980, 3370, 4825 and
 328 5104 m for MEMV, MESV, SEMV and SESV, respectively. This range is extended when modelled
 329 over high vegetation (i.e. woodlands) occurring within 5227, 5259, 7504, and 7705 m from the
 330 farm border for MEMV, MESV, SEMV and SESV. This information is visualised in contours
 331 presented in Appendix 2, alongside Table 3.

332 The maximum distance downwind of the farm where 1% of critical levels were exceeded were
 333 27.4 and 6.8 km; where 4% was exceeded within 5.2 and 2.9 km for 1 µg m⁻³ and 3 µg m⁻³
 334 respectively. The extent of models incorporating SCAIL-Agriculture rates also spread much

335 farther compared to monitored rates; the most significant of which is SESV which predicts 1% of
336 $1 \mu\text{g m}^{-3}$ being reached as far as 32 km downwind, reducing to 30.3 km for SEMV and 27.6 km
337 for MESV.

338 The model outputs presented in Table 3 were normalised using standard normal variate
339 transformation (Rinnan et al., 2009) and analysed using t-Tests (paired two sample for means)
340 (Ruxton & Neuhäuser, 2010) This was intended to compare the significance of altered model
341 inputs on the maximum concentration and deposition extents. The output from t-Tests are
342 presented in Table 4. P-values for one tailed and critical levels were below 0.01 for all models,
343 indicating that when normalised the maximum extents modelled by AERMOD were significantly
344 different. The level of significance varied between models, with the model generated using both
345 SCAIL-Agriculture emission and ventilation rates having a more significant difference to the
346 model generated using monitored rates, than any other combination. Altering the emission rate
347 had a more significant effect than altering the ventilation rate, while altering both had the most
348 significant effect. The increasing difference between model outputs is also represented by the
349 increasing difference between t-Stat and the t-Critical two-tail values presented in Table 4. This
350 difference increases from 1.46 to 19.09 to 27.15 for MESV, SEMV and SESV respectively.

351

352

353 **Table 4. Output from T-test comparing statistical significance of modelled scenarios extent**
 354 **difference from Monitored Emissions & Monitored Ventilation (MEMV).**

	Observations	Pearson Correlation	Hypothesized Mean Difference	df	t Stat	P(T<=t) one-tail	t Critical one-tail
Monitored Emissions & SCAIL Ventilation (MESV)	9	-0.96	0	8	3.77	2.72E-03	1.86
SCAIL Emissions & Monitored Ventilation (SEMV)	9	0.65	0	8	21.4	1.19E-08	1.86
SCAIL Emissions & Ventilation (SESV)	9	0.1	0	8	29.46	1E-09	1.86

355

356 The difference between model outputs summarised as percentages is presented in Table 5,
 357 where the use of the SCAIL-Agriculture ventilation rate increased the dispersion extent for
 358 modelled concentrations between 0.6 – 27.1%, on average 14.1%. Using the SCAIL-Agriculture
 359 emission rate increased this difference to a range of 26.2 – 62.5%, on average 38.2%. The
 360 greatest dispersion extent was observed when both SCAIL-Agriculture emission and ventilation
 361 rates were used with a difference of between 16.7 – 71.3% compared to the monitored data,
 362 with an average difference of 50.9%.

363

364

365 **Table 5. Percent differences of model outputs compared to models produced using monitored**
 366 **emission and ventilation rates (MEMV).**

NH ₃ Concentration (µg m ⁻³)	Dry Deposition (kg N ha ⁻¹ yr ⁻¹)		% Greater than Monitored Emissions & Ventilation (MEMV)		
	Other	Woodland	Monitored Emissions & SCAIL Ventilation (MESV)	SCAIL Emissions & Monitored Ventilation (SEMV)	SCAIL Emissions & Ventilation (SESV)
0.01	0.05	0.08	0.8	10.6	16.7
0.03	0.16	0.23	12.8	37.5	41.9
0.04	0.2	0.3	0.6	43.6	47.4
0.06	0.3	0.5	13.1	61.9	71.3
0.12	0.6	0.9	14.8	62.5	70.6
1	5.2	7.8	17.6	28.2	50
3	15.6	23.4	27.1	35.6	64.4
5	25.9	39	26.2	26.2	45.2
Average			14.1	38.3	50.9

367

368 **4. Discussion**

369 **4.1. Emission monitoring**

370 Monitoring conducted as part of this study indicated an overall average NH₃ emission rate of
 371 0.25 g bird⁻¹ day⁻¹. Emission rates had a strong association with ambient temperature, where
 372 average temperatures of 3.67, 5.6, 15.46 and 15.29°C for February, March, July and August
 373 elicited emission rates of 0.16, 0.23, 0.33 and 0.27 g bird⁻¹ day⁻¹, respectively. Previous work on
 374 NH₃ emissions from laying hen units in Ireland has also shown seasonally variable NH₃ emission
 375 rates, where 0.1 g bird⁻¹ day⁻¹ was observed in spring for a battery caged house with manure
 376 removal, and 0.5 g bird⁻¹ day⁻¹ for summer emissions from a laying hen house with a deep pit
 377 (Hayes et al., 2006). As the monitoring by Hayes et al. (2006) was carried out on two different

378 house types, the full influence of temperature was not apparent at the time. Though not directly
379 comparable to monitoring conducted in this study due to different housing types, monitored
380 spring emissions were higher than those observed from the battery cage at $0.20 \text{ g bird}^{-1} \text{ day}^{-1}$
381 and lower than summer emissions from the deep pit at $0.29 \text{ g bird}^{-1} \text{ day}^{-1}$. Emission rates
382 reported for laying hens in battery cages ranged from 0.03 to $0.47 \text{ g bird}^{-1} \text{ day}^{-1}$ in Germany and
383 England respectively (Groot Koerkamp et al., 1998). This shows a significant diversity of emission
384 rates for battery cages within different countries, however battery cages are currently illegal
385 throughout Europe under Council Directive (1999/74/EC)(European Commission, 1999).

386 The UK emissions inventory provides a mean emission factor of $60 \text{ g NH}_3 \text{ day}^{-1} \text{ LU}^{-1}$ (Livestock
387 Unit), while they use a weighted average of $50.4 \text{ g NH}_3 \text{ day}^{-1} \text{ LU}^{-1}$ (Misselbrook et al., 2016). This
388 is equivalent to $0.19 - 0.23 \text{ g bird}^{-1} \text{ day}^{-1}$. The Irish inventory reported an emission rate of 132.5
389 $\text{g day}^{-1} \text{ LU}^{-1}$ for caged laying hens in 2003 (Hyde et al., 2003), which is equivalent to 0.5 g bird^{-1}
390 day^{-1} . Hyde et al., (2003) stated that the emission factors used for Irish poultry houses differ
391 from the UK figures due to a difference in average weight class categories used. Data provided
392 to this study from the EPA identify the use of an emission rate of $0.42 \text{ g bird}^{-1} \text{ day}^{-1}$ (Hyde, 2013,
393 pers. comm). National inventory reporting currently differs to Annual Environmental Report /
394 Pollutant Release and Transfer Register reporting, where emission factors are no longer used to
395 calculate emissions. Instead, the national inventory is currently based on the quantity of
396 nitrogen excreted by livestock and the availability of the nitrogen excreted for volatilisation as
397 NH_3 (Hyde, 2018, pers. comm).

398 BAT Annual Emission Limits for laying hens are set between 0.05 to $0.22 \text{ g bird}^{-1} \text{ day}^{-1}$ for caged
399 laying hens, which increases to $0.68 \text{ g bird}^{-1} \text{ day}^{-1}$ if manure drying such as that carried out on
400 the monitored farm is applied (European Commission, 2017). Emission rates reported for a similar
401 house in Spain were 0.14 and $0.09 \text{ g bird}^{-1} \text{ day}^{-1}$ in the summer and winter, respectively. These
402 rates are likely lower than those monitored by this study as manure was removed via conveyor

403 belts every 3 – 5 days, unlike every seven days on the monitored farm (Alberdi et al., 2016).
404 Emission rates varied throughout the week during this monitoring programme, where they were
405 highest on Sunday at $0.35 \text{ g bird}^{-1} \text{ day}^{-1}$ and lowest on Wednesday at $0.11 \text{ g bird}^{-1} \text{ day}^{-1}$. This was
406 due to the build-up of manure during the week prior to removal on Tuesdays. This supports the
407 concept that more frequent manure removal reduces emissions. A study in the United States
408 also showed a daily ammonia emission rate of $0.14 \pm 1 \text{ g bird}^{-1} \text{ day}^{-1}$ which is comparable to other
409 manure belt caged houses in the US, but lower than high rise cage houses (Zhao et al., 2013).
410 The farm in Zhao's study utilised recirculated air to dry the manure and also removed manure
411 every three days. Similarly, the standardised rate in the Netherlands for NH_3 emission rate is 0.1
412 $\text{g bird}^{-1} \text{ day}^{-1}$ (Groot Koerkamp et al., 1998), which is likely achieved by increasing frequency of
413 manure removal. Altering the frequency of manure removal has the potential to influence how
414 dry the manure is prior to storage, which may influence emissions following removal from the
415 house.

416 The ventilation rate of $931 \text{ cm}^3 \text{ s}^{-1} \text{ bird}^{-1}$ in this study was higher than the equivalent rate of 690
417 $\text{cm}^3 \text{ s}^{-1} \text{ bird}^{-1}$ recommended by SCAIL-Agriculture (Hill et al., 2014), which was derived from
418 previous research (Seedorf et al., 1998). There was a substantial difference in ventilation rate
419 observed in the cold and warm periods, with 641 and $1237 \text{ cm}^3 \text{ s}^{-1} \text{ bird}^{-1}$, respectively; both of
420 which are higher than the relevant rates recommended in SCAIL-Agriculture, of 560 and 830 cm^3
421 $\text{s}^{-1} \text{ bird}^{-1}$ for winter and summer. It has been previously pointed out that increasing ventilation
422 rates increases emissions, and modern houses focusing on animal welfare reducing indoor
423 concentrations may be as a direct result increasing their emissions (Ndegwa et al., 2008).

424 As the exceedance of annual critical levels is the most precautionary approach to protect
425 habitats and species (Sutton et al., 2008), the annual average emission and ventilation rates are
426 the most suitable factor for environmental conservation. The detailed monitoring conducted
427 will benefit future studies, providing valuable information on diurnal and seasonal variations in

428 emissions. BAT guidance suggests laying hens have stable emission patterns and suggests
429 splitting six sampling days within the year to one randomly selected day every two months
430 (European Commission, 2017). This work has shown that in houses with belt removal of manure
431 this is not sufficient, as a linear increase in emissions after manure removal would need to be
432 considered when monitoring emission rates which vary depending on frequency of manure
433 removal. The approach recommended for pigs or broilers may be more appropriate, but on a
434 smaller scale as broilers undergo much longer periods of increases (from 0 to 37 days) compared
435 to a weekly laying hen cycle of emissions observed on this farm.

436 **4.2. Concentration Modelling**

437 The extent to which contours were modelled was determined by pre-selected values, intending
438 to represent concentration and deposition rates relevant to negative ecological effects.
439 Modelling of both concentration and dry deposition was intended to mimic the process used in
440 SCAIL-Agriculture, which intentionally excludes dry depletion of ammonia, and chemical
441 conversion followed by wet deposition as ammonium (Hill et al., 2014). The SCAIL-Agriculture
442 report indicates that excluding both depletion and atmospheric transformation results in an
443 overestimation of impacts by c. 10%, which for the purposes of AA screening is considered
444 precautionary (Hill et al., 2014). Monitoring and modelling for this study was only conducted on
445 the bird housing; the dry manure store adjacent to these houses was excluded. Housing was
446 estimated to contribute 70% of national emissions for poultry in Ireland, where storage accounts
447 for only 3% (Hyde et al. 2003). As the manure had been dried, its anticipated contribution should
448 be minimal, though even a small contribution should not be discounted in the AA process.

449 The highest concentration modelled was $8 \mu\text{g m}^{-3}$, intended to represent acute negative
450 ecological effects observed on Moninea bog from contributions of the farm alone (Sutton, 2007).
451 This concentration was not observed when modelling was conducted using only the monitored
452 rates, but was for every other modelled scenario. The use of SCAIL-Agriculture emission and

453 ventilation rates (SESV) indicated this concentration could occur 95 m downwind from the farm
454 border. As it is unlikely that any farm would be situated in an area with no ambient concentration
455 of ammonia, $5 \mu\text{g m}^{-3}$ was also modelled. This was intended to represent the area within which
456 acute effects could be observed, including the highest ambient concentration monitored in
457 Ireland: $3.21 \mu\text{g m}^{-3}$ (de Kluizenaar and Farrell, 2000). Depending on model inputs, this
458 concentration was predicted to occur within 84 – 122 m downwind of the farm border. Critical
459 levels of 1 and $3 \mu\text{g m}^{-3}$ were exceeded within 312 – 468 m and 118 – 194 m respectively,
460 depending on model inputs. These exceedances are representative of contributions from the
461 farm housing alone, as the highest recorded ambient baseline concentration already exceeds
462 these critical levels.

463 **4.3. Influence of Emission and Ventilation Rates**

464 A statistically significant difference was observed between monitored data, and all modelled
465 outputs using SCAIL-Agriculture emission and ventilation rates. Though all outputs were
466 significantly different, the level of significance varied depending on model inputs used. Use of
467 the SCAIL-Agriculture emission rate had a greater influence on the model output compared to
468 using the SCAIL-Agriculture ventilation rate. The difference between the model outputs were
469 summarised as percent greater than the models generated using monitored data, the model
470 output created using the SCAIL-Agriculture emission rate was on average 38.2% greater than the
471 one created using only monitored data, where the model created using the SCAIL-Agriculture
472 ventilation rate was on average 14.1% greater. The greatest difference was observed when use
473 of both the SCAIL-Agriculture emission and ventilation rates were used, with a 50.9% difference
474 on average. This validates the use of SCAIL-Agriculture emission and ventilation rates for
475 screening potential effects as part of stage 1 AA where a precautionary approach is required. If
476 a more detailed assessment is required as part of stage 2 AA, detailed emission monitoring could
477 produce rates which could reduce the number of Natura 2000 sites modelled to be included in

478 an AA. This study does not recommend using emission and ventilation rates monitored for this
479 house to conduct environmental assessments as these factors are based from a study in a single
480 house. Development of emission and ventilation factors such as those used in SCAIL-Agriculture
481 are based on numerous studies, to which this study is intended to contribute.

482 **4.4. Determining Ecological Impacts**

483 In reality, ambient or baseline concentrations would need to be considered when determining
484 ecological impacts from such a farm. These can be highly spatially variable (Singles et al., 1998),
485 with monitored ranges in Ireland of 0.18 – 3.21 $\mu\text{g m}^{-3}$ (de Kluizenaar and Farrell, 2000), 0.48 –
486 2.96 $\mu\text{g m}^{-3}$ (Doyle et al., 2017) and 0.5 – 4.6 $\mu\text{g m}^{-3}$ (Kelleghan et al., 2020). These three studies
487 monitored different locations across Ireland, highlighting the spatial variation that occurs in
488 concentration due to agricultural activity. A baseline concentration may differ from ambient as
489 it is intended to include contributions from other hotspot sources, i.e., all sources excluding
490 contributions from a proposed development (IAQM, 2019). Ambient monitoring conducted in
491 Ireland (Doyle et al., 2017; de Kluizenaar and Farrell, 2000) intentionally excluded monitoring
492 within 2 km from hotspot sources, and as such is not representative of concentrations where
493 these sources occur. Similarly, in the UK where emissions, concentration and deposition are
494 averaged over 1 or 5 km grids (Hallsworth et al., 2010), potential contributions of such hotspot
495 sources may be underpredicted. When performing an AA on a Natura 2000 site contribution to
496 local concentration and deposition of the new development should be assessed in combination
497 with the baseline concentration, not the ambient. Modelled ambient concentrations across
498 Ireland indicate a range of 0.38 – 4.47 $\mu\text{g m}^{-3}$ (Kelleghan et al., 2019), indicating exceedance of
499 critical levels on Natura 2000 sites of 80.1% for concentrations of 1 $\mu\text{g m}^{-3}$ and 5.9% exceeding 3
500 $\mu\text{g m}^{-3}$. Considering 34.3 % of Natura 2000 sites exceed 2 $\mu\text{g m}^{-3}$, contributing an additional 1 μg
501 m^{-3} within 312 – 468 m as identified within this study, could contribute to the baseline
502 concentration exceeding the critical level for higher plants.

503 The European Union Network for the Implementation and Enforcement of Environmental Law
504 (IMPEL) had previously set the *de minimis* value for contributions to dry deposition of nitrogen
505 from hotspot NH₃ sources at 0.3 kg N ha⁻¹ year⁻¹. The IMPEL guidance states, below this
506 deposition rate contributions “cannot be realistically attributed to a particular project they
507 should rather be described as diffuse part of the background deposition”. However, The Dutch
508 Nitrogen Case (C 293/17 & C 294/17)(CJEU, 2019) clarifies any additional contribution, even
509 below previously identified *de minimis* values may contribute towards a Natura 2000 site not
510 achieving favourable conservation status. In this instance, the Dutch Nitrogen Case is referring
511 to sites which have already exceeded their site-specific critical thresholds. Hence, if a site is
512 already impacted in the eyes of the European Court of Justice, any additional contribution could
513 be considered a significant impact under the Habitats Directive (92/43/EEC) regardless of how
514 minute.

515 This study modelled the dispersion extent at which IMPEL’s *de minimis* threshold to deposition
516 occurred. Dry deposition was modelled using the two deposition velocities provided in SCAL-
517 Agriculture, intended to represent deposition across woodland and other surfaces (Hill et al.,
518 2014). Modelling indicated IMPEL’s *de minimis* values from laying hen housing occurred within
519 2.9 – 5.1 km and 5.2 – 7.7 km for other surfaces and woodland, respectively. For every model
520 produced, such deposition only occurred within the 10 km distance threshold (currently used by
521 Ireland’s National Parks and Wildlife Service (NPWS, 2009) to screen potential effects on Natura
522 2000 sites). However, a 5 km distance threshold used by some organisations would have failed
523 to adequately account for potential contribution to impacts (Environment Agency, 2018).

524 The United Kingdom uses a percentage of process contribution to indicate significance of effects
525 on Natura 2000 sites to trigger when a stage 2 AA is required. Originally it was envisioned within
526 the UK that the contribution of 1 – 4% of a critical level or load was not significant alone or in
527 combination (Hicks et al., 2011). Since then, advice has been changing in line with outcomes of

528 national court cases, and is likely non-compliant with the Habitats Directive (92/43/EEC)
529 (European Economic Committee, 1992) based on the findings of the Dutch Nitrogen Case (C
530 293/17 & C 294/17)(CJEU, 2019). Guidance currently out for consultation by Natural Resources
531 Wales indicates that the currently used 1% threshold is not adequate to screen effects from “in-
532 combination assessments”. It remains to be seen how this updated guidance will influence
533 cumulative impact assessments, a requirement of the Habitats Directive (92/43/EEC) (European
534 Economic Committee, 1992) for every Appropriate Assessment. This guidance goes on to clarify,
535 where a habitat is particularly sensitive to negative effects from atmospheric NH₃ or nitrogen
536 deposition, contributions below 1% may be considered significant (Natural Resources Wales,
537 2020). The maximum distance an exceedance of 1% was modelled from the current study ranged
538 from 27.4 to 32 km depending on inputs, a difference in 4.5 km could easily influence the
539 approval of local authority planning applications, highlighting the need for detailed monitoring
540 to ensure the most appropriate emission and ventilation rates are being used to model effects
541 on the environment. In practice, including Natura 2000 sites 22.2 – 24.5 km away in an NH₃
542 impact assessment is counter intuitive, as due to the low dispersion potential of NH₃ it is typically
543 dry deposited near the source (Krupa, 2003; Pitcairn et al., 2002). Atmospheric dispersion
544 models such as AERMOD (utilised by the SCAIL-Agriculture tool) predict the dispersion of a
545 pollutant into the atmosphere along a gradient until it eventually reaches a zero concentration.
546 The percent threshold currently recommended within the UK of 1% for sensitive Natura 2000
547 sites (critical level of 1 µg m⁻³) extends as far as 27.4 km for monitored data downwind.
548 Therefore, using the percent thresholds for stage 1 screening of this farm would potentially
549 require detailed stage 2 assessment for any Natura 2000 containing sensitive conservation
550 features such as bogs, heath or Atlantic oak woodlands within 27.4 km from the farm. The
551 application of IMPEL’s *de minimis* 0.3 kg N ha⁻¹ year⁻¹ would include sites within 5.2 and 2.9 km
552 for woodlands and other habitats, respectively. For this example, the potential difference in the
553 use of both thresholds ranges from 22.2 – 24.5 km. In practice, this could result in an over-

554 precautionary approach assessing impacts across a greater range than they potentially occur. If
555 IMPEL guidance is followed and “only project contributions above the cut off criterion (0.3 kg N
556 ha⁻¹ year⁻¹) have to be considered within appropriate assessment in combination with other
557 projects” (IMPEL, 2017), the UK’s percent thresholds may be over-precautionary. In this case,
558 stage 2 AA should only be triggered when modelled deposition on a Natura 2000 site exceeds
559 0.3 kg N ha⁻¹ year⁻¹, or is in receipt of equivalent concentrations (0.04 & 0.06 µg m⁻³ depending
560 on deposition velocity used). This also applies to the findings of the Dutch Nitrogen Case which
561 requires AA for any contribution, even below previously identified *de minimis* contributions,
562 where the lower the concentration screened the greater the model extent.

563 Following chemical transformation to particulate matter as ammonium (NH₄), it can spread
564 much greater distances and potentially impact Natura 2000 sites via wet deposition. This wet
565 deposition, however, is not what these models in practice assess, as they would require different
566 model parameters and model set up. Hence, using a 1% threshold or lower for the requirement
567 of a stage 2 AA may not be additionally precautionary, unless limited by a distance threshold.
568 Recommendations from the Dutch Nitrogen Case (C 293/17 & C 294/17)(CJEU, 2019) have
569 clarified that unless detailed baseline conditions, inclusive of contributions from local hotspot
570 sources are understood, the trigger should be set based on any contribution to the Natura 2000
571 site. Authors of this paper recognise, that unless factors such as chemical transformation and
572 dry depletion are included in screening models, a distance threshold for exceedance should be
573 recommended, as the dispersion potential for NH₃ is limited. A better understanding of all
574 contributing sources of NH₃ on Natura 2000 sites would benefit such assessments, identifying
575 sites close to or already exceeding their critical level or load.

576 **4.5. Influence of Meteorological Data**

577 Meteorological data influences predicted concentrations and extents from dispersion models,
578 based both on the source of data and the period modelled. This study utilised data from the

579 nearest synoptic meteorological station, though conditions are likely to vary on the site due
580 primarily to topographical differences between sites (Ulman et al., 2005). In practice, when
581 carrying out modelling assessments meteorological data 35 km from the point of interest would
582 likely be not representative of local conditions (Environmental Protection Agency, 2019). As in
583 this case, modelling was intended to act as a case study of conditions from a farm which could
584 be located anywhere in the country; as such the inclusion of any long term monitored
585 meteorological data would be appropriate. The full meteorological year is required when
586 modelling the annual exceedance of critical levels and loads, in order to account for the full
587 effect of seasonal variation both of emissions and meteorological conditions. Modelling
588 conducted by Kelleghan et al. (2020) validates the requirement of modelling multiple years
589 when conducting an environmental assessment. Previously, it has been recommended that
590 when conducting an environmental assessment, modelling should be conducted separately for
591 the five most recent years and the outcome predicting the worst impacts be applied
592 (Environment Agency, 2010). Kelleghan et al. (2020) notes that this could include both the year
593 with maximum dispersion potential and the year with the lowest, due to potentially increased
594 local levels of concentration and deposition. Though dispersion of NH₃ can vary significantly
595 throughout the day and over seasons, the use of annual exceedances is more precautionary than
596 over any other time period (Sutton et al., 2008). As such, this should be paired with
597 representative annual meteorological conditions, considering the worst-case scenario for
598 potential impacts.

599 **4.6. Emission & Impact Reduction**

600 The management system used by this particular laying hen house, by drying and continuously
601 removing manure enhances the farm's ability to control emissions and subsequent contributions
602 to local concentrations and deposition. By increasing the frequency of manure removal, the
603 contribution of emissions from the house can be effectively managed and potentially reduced.
604 However, consideration should be given to how this influences emissions from the dry manure

605 store. As the manure is dried prior to storage, it is likely to reduce environmental impacts
606 compared to wet manure; which has a much higher emission rate (Meisinger & Jokela, 2000).
607 The protein content in the feed at 16% is already considered to be a very low concentration
608 (Nahm, 2003), with research showing reducing by an additional percentage has an observable
609 influence on emissions (Roberts, 2007). However, Roberts' study showed that increasing the
610 dietary fibre could also further enhance emission reductions. Planting woodland as a barrier to
611 NH₃ emissions is a potential measure to mitigate unwanted effects downwind (Tyndall, 2008;
612 Jerez, et al., 2016). If dry deposition is encouraged in planted woodlands near the farm, it can
613 reduce downwind impacts to potentially sensitive sites. Any methods for reducing emissions will
614 also contribute to reductions in local concentrations and deposition, thereby decreasing
615 potential ecological effects. Reducing emissions therefore has benefits both for compliance with
616 the EU NEC (2016/2284/EU) and Habitats Directives (92/43/EEC) (European Economic
617 Committee, 1992).

618

619 **5. Conclusions**

620 This study monitored the NH₃ emission and ventilation rates for one enriched caged laying hen
621 house in Ireland. The emission rates showed substantial seasonal, weekly and daily variation,
622 with an overall average NH₃ emission rate of 0.25 g bird⁻¹ day⁻¹. The average ventilation rate was
623 931 cm³ s⁻¹ bird⁻¹. Monitoring indicated that increasing the frequency of manure removal is an
624 effective method of reducing emissions, which increase every day until manure is removed via
625 conveyor belt.

626 The maximum extent of modelled concentrations using monitored and SCAIL-Agriculture rates
627 were significantly different. The use of SCAIL-Agriculture emission and ventilation rates would
628 have been suitable for Appropriate Assessment of this farm, as including the emission and / or
629 ventilation rate resulted in significantly greater ammonia dispersion extents. Detailed emission
630 and ventilation monitoring could be conducted on a site-specific basis in order to improve
631 predictions of potential negative ecological effects. Additionally, this highlights the use of a
632 higher emission rate and lower ventilation rate may generate more precautionary models for
633 Appropriate Assessment.

634 Deciding what contribution from a hotspot source such as a layer farm elicits as a potential
635 significant effect on a Natura 2000 site is a contentious issue. The outcome from the Dutch
636 Nitrogen Case (C 293/17 & C 294/17) identifies any contribution, even below the previously
637 presumed *de minimis* 0.3 kg N ha⁻¹ yr⁻¹ could result in an inability of a Natura 2000 site to meet
638 its conservation objective. The use of percent thresholds as a trigger for requiring a detailed AA
639 is in direct conflict with this decision, as it excludes assessment of baseline conditions. Modelling
640 however also needs to give cognisance to the dispersion potential of NH₃ as modelling such low
641 concentrations substantially expands the extent modelled, increasing the number of Natura
642 2000 sites included in the assessment. A more appropriate approach may be to use any
643 exceedance within a set distance from the source as a trigger for full AA.

644 **6. Acknowledgements**

645 This research was undertaken as part of the AmmoniaN2K Project funded by the Irish
646 Environmental Protection Agency through their STRIVE Programme. The authors also wish to
647 acknowledge the support of the AmmoniaN2K Project Steering Committee. Though the farm on
648 which monitoring was undertaken has been anonymised, the AmmoniaN2K project owe a great
649 debt to the farmer who agreed to allow monitoring on an active farm. The authors would also
650 like to thank Dr. Ronan Dorrepaal and Ms. Emma Jane Wade for advice provided.

651 **7. References**

- 652 Alberdi, O., Arriaga, H., Calvet, S., Estellés, F. & Merino, P. 2016. Ammonia and greenhouse gas
653 emissions from an enriched cage laying hen facility. *Biosystems Engineering*, 144, 1-12.
- 654 Anker, H.T., Backes, C.W., Baaner, L., Keessen, A.M. and Möckel, S., 2019. Natura 2000 and the
655 regulation of agricultural ammonia emissions. *Journal for European Environmental &*
656 *Planning Law*, 16(4), pp.340-371.
- 657 Baker, J., Battye, W.H., Robarge, W., Arya, S.P. and Aneja, V.P., 2020. Modeling and
658 measurements of ammonia from poultry operations: Their emissions, transport, and
659 deposition in the Chesapeake Bay. *Science of The Total Environment*, 706, p.135290.
- 660 Bobbink, R., Hettelingh, J. P., 2011. Review and revision of empirical critical loads and dose-
661 response relationships: Proceedings of an expert workshop, Noordwijkerhout, 23-25
662 June 2010. Rijksinstituut voor Volksgezondheid en Milieu RIVM.
- 663 CJEU, 2019. Judgment: Joined Cases C-293/17 and C-294/17 Coöperatie Mobilisation for the
664 Environment UA, Vereniging Leefmilieu v College van gedeputeerde staten van Limburg,
665 College van gedeputeerde staten van Gelderland [2018].
- 666 De Kluizenaar, Y. & Farrell, E. P. 2000. Ammonia Monitoring In Ireland: A Full Year Of Ammonia
667 Monitoring. R&D Report Series No. 8. Dublin: Forest Ecosystem Research Group,
668 University College Dublin, 66.

669 De Sadeleer, N. 2009. The Precautionary Principle as a Device for Greater Environmental
670 Protection: Lessons from EC Courts. *Review of European Community & International*
671 *Environmental Law*, 18, 3-10.

672 Department of Agriculture Food and the Marine 2015. *Food Wise 2025*. Department of
673 Agriculture Food and the Marine, Dublin, Ireland.

674 Doyle, B., Cummins, T., Augustenborg, C. & Aherne, J. 2017. *Ambient Atmospheric Ammonia in*
675 *Ireland, 2013-2014*. Environmental Protection Agency, Wexford, Ireland.

676 Environment Agency, 2010. *Guidance on modelling the concentration and deposition of*
677 *ammonia emitted from intensive farming*. Available: [http://www.environment-](http://www.environment-agency.gov.uk/business/sectors/40071.aspx)
678 [agency.gov.uk/business/sectors/40071.aspx](http://www.environment-agency.gov.uk/business/sectors/40071.aspx). Last accessed 01/06/2020

679 Environment Agency, 2018. *Intensive farming risk assessment for your environmental permit*.
680 Available: [https://www.gov.uk/guidance/intensive-farming-risk-assessment-for-your-](https://www.gov.uk/guidance/intensive-farming-risk-assessment-for-your-environmental-permit)
681 [environmental-permit](https://www.gov.uk/guidance/intensive-farming-risk-assessment-for-your-environmental-permit). Last accessed 01/06/2020.

682 Environmental Protection Agency, 2019. *Air Dispersion Modelling from Industrial Installations*
683 *Guidance Note (AG4)*. Environmental Protection Agency, Johnstown Castle, Wexford,
684 Ireland.

685 European Commission 1999. *Council directive 1999/74/EC of 19 July 1999 laying down minimum*
686 *standards for the protection of laying hens*. *Official Journal of the European*
687 *Communities*. Brussels, Belgium.

688 European Commission 2009. *Directive 2009/147/EC of the European parliament and of the council*
689 *of 30 November 2009 on the conservation of wild birds*. *Official Journal of the European*
690 *Communities*. Brussels, Belgium.

691 European Commission. 2017. *Commission implementing decision (EU) 2017/302 of 15 February*
692 *2017 establishing best available techniques (BAT) conclusions, under directive*
693 *2010/75/EU of the European Parliament and of the Council, for the intensive rearing*

694 ofpoultry or pigs. [Online]. Available: <http://eippcb.jrc.ec.europa.eu/reference/>
695 [Accessed 12 July 2018].

696 European Commission 2013. Best Available Techniques (BAT) Reference Document for the
697 Intensive Rearing of Poultry and Pigs. JRC Science for Policy Report, Brussels, Belgium.

698 European Economic Committee 1992. Council directive 92/43/EEC of 21 May 1992 on the
699 conservation of natural habitats and of wild fauna and flora. Official Journal of the
700 European Communities. Brussels, Belgium.

701 European Environment Agency. 2017. National emissions reported to the Convention on Long-
702 range Transboundary Air Pollution (LRTAP Convention) [Online]. European Environment
703 Agency. Available: [https://www.eea.europa.eu/data-and-maps/data/national-](https://www.eea.europa.eu/data-and-maps/data/national-emissions-reported-to-the-convention-on-long-range-transboundary-air-pollution-lrtap-convention-11)
704 [emissions-reported-to-the-convention-on-long-range-transboundary-air-pollution-](https://www.eea.europa.eu/data-and-maps/data/national-emissions-reported-to-the-convention-on-long-range-transboundary-air-pollution-lrtap-convention-11)
705 [lrtap-convention-11](https://www.eea.europa.eu/data-and-maps/data/national-emissions-reported-to-the-convention-on-long-range-transboundary-air-pollution-lrtap-convention-11) [Accessed 16/01/2018 2017].

706 European Union 2010. Directive 2010/75/EU of the European parliament and of the council of
707 24 November 2010 on industrial emissions (integrated pollution prevention and
708 control). Official Journal of the European Union, Brussels, Belgium.

709 European Union 2016. Directive (EU) 2016/2284 of the european parliament and of the council
710 of 14 December 2016 on the reduction of national emissions of certain atmospheric
711 pollutants, amending Directive 2003/35/EC and repealing Directive 2001/81/EC. Official
712 Journal of the European Union, Brussels, Belgium.

713 Food and Agriculture Organization 2014. FAO statistical yearbook 2014 europe and central asia
714 food and agriculture. Food and Agriculture Organization of the United Nations Regional
715 Office for Europe and Central Asia. Budapest, Hungary.

716 Groot Koerkamp, P. W. G., Metz, J. H. M., Uenk, G. H., Phillips, V. R., Holden, M. R., Sneath, R.
717 W., Short, J. L., White, R. P. P., Hartung, J., Seedorf, J., Schröder, M., Linkert, K. H.,
718 Pedersen, S., Takai, H., Johnsen, J. O. & Wathes, C. M. 1998. Concentrations and

719 Emissions of Ammonia in Livestock Buildings in Northern Europe. *Journal of Agricultural*
720 *Engineering Research*, 70, 79-95.

721 Hadlocon, L.S., Zhao, L.Y., Bohrer, G., Kenny, W., Garrity, S.R., Wang, J., Wyslouzil, B., Upadhyay,
722 J., 2015. Modeling of particulate matter dispersion from a poultry facility using
723 AERMOD. *Journal of Air & Waste Management Association* 65, 206–217.
724 <https://doi.org/10.1080/10962247.2014.986306>

725 Hallsworth, S., Dore, A.J., Bealey, W.J., Dragosits, U., Vieno, M., Hellsten, S., Tang, Y.S., Sutton,
726 M.A., 2010. The role of indicator choice in quantifying the threat of atmospheric
727 ammonia to the 'Natura 2000' network. *Environmental Science Policy* 13, 671–687.
728 <https://doi.org/https://doi.org/10.1016/j.envsci.2010.09.010>

729 Hayes, E. T., Curran, T. P. & Dodd, V. A. 2006. Odour and ammonia emissions from intensive
730 poultry units in Ireland. *Bioresource Technology*, 97, 933-939.

731 Hicks, W. K., Whitfield, C.P., Bealey, W.J. , & Sutton M.A., 2011. Nitrogen Deposition and Natura
732 2000 Science and Practice in Determining Environmental Impacts.
733 COST729/Nine/ESF/CCW/JNCC/SEI Work. Proceedings, Publ. by COST. Available [http//](http://cost729.ceh.ac.uk/n2kworkshop)
734 cost729.ceh.ac.uk/n2kworkshop.

735 Hill, R., Bealey, B., Johnson, C., Ball, A., Simpson, K., Smith, A., Theobald, M. R., Braban, C. F.,
736 Magaz, I. & Curran, T. P. 2014. SCAIL-Agriculture update. Sniffer ER26 Final Report.

737 Huang, D. and Guo, H., 2019. Dispersion modeling of odour, gases, and respirable dust using
738 AERMOD for poultry and dairy barns in the Canadian Prairies. *Science of The Total*
739 *Environment*, 690, pp.620-628.

740 Hyde, B. P., 2013. RE: Personal Communication.

741 Hyde, B. P., 2018. RE: Personal Communication.

742 Hyde, B. P., Carton, O. T., O'Toole, P. & Misselbrook, T. H. 2003. A new inventory of ammonia
743 emissions from Irish agriculture. *Atmospheric Environment*, 37, 55-62.
744 [https://doi.org/http://doi.org/10.1016/S1352-2310\(02\)00692-1](https://doi.org/http://doi.org/10.1016/S1352-2310(02)00692-1)

745 IAQM (2019). A guide to the assessment of air quality impacts on designated nature
746 conservation sites. Institute of Air Quality Management, London, United Kingdom.

747 IMPEL, 2017. Nature protection in permitting and inspection of industrial installations –
748 Implementation of Art. 6(3) of the Habitats Directive (Phase 3). Development of IMPEL
749 guidance document, pig and poultry farms and Natura 2000 and updated wind energy
750 development case studies. European Union Network for the Implementation and
751 Enforcement of Environmental Law. 2015/4.

752 Jerez, S. B., Bray, J., Austin, S., F. 2016. Demonstrating the effect of trees for controlling
753 particulate matter, ammonia, and odor from poultry buildings. Final project report.
754 United States Department of Agriculture. Texas, United States.

755 Kelleghan, D.B., Hayes, E.T., Everard, M., Curran, T.P (2020). Assessment of the impact of
756 ammonia emissions from intensive agriculture installations on SACs and SPAs.
757 Environmental Protection Agency, Wexford, Ireland.

758 Kelleghan, D.B., Hayes, E.T., Everard, M., Curran, T.P., 2019. Mapping ammonia risk on sensitive
759 habitats in Ireland. *Sci. Total Environ.* 649, 1580–1589.
760 <https://doi.org/https://doi.org/10.1016/j.scitotenv.2018.08.424>

761 Koerkamp, P. G. 1998. Review on emissions of ammonia from housing systems for laying hens
762 in relation to sources, processes, building design and manure handling. *Journal of*
763 *Agricultural Engineering Research*, 59, 73-87.

764 Krupa, S. V. 2003. Effects of atmospheric ammonia (NH₃) on terrestrial vegetation: a review.
765 *Environmental Pollution*, 124, 179-221.

766 Leonard, A. 2014. RE: Personal Communication.

767 Li, H., Xin, H., Liang, Y., Gates, R. S., Wheeler, E. F. & Heber, A. J. 2005. Comparison of direct vs.
768 indirect ventilation rate determinations in layer barns using manure belts. Transactions
769 of the ASABE, 48, 367-372.

770 Meisinger, J. & Jokela, W. 2000. Ammonia volatilization from dairy and poultry manure.
771 Proceedings from managing nutrients and pathogens from animal agriculture, 334-354.

772 Misselbrook, T., Gilhespy, S., Cardenas, L., Williams, J. & Dragosits, U. 2016. Inventory of
773 Ammonia Emissions from UK Agriculture 2015. Department for Environment, Food &
774 Rural Affairs.

775 Mosquera, J., Groenestein, K., Ogink, N. & Aarnink, A. Evaluation of the CO₂ mass balance
776 method to calculate ventilation rates from mechanically ventilated livestock buildings.
777 The Ninth International Livestock Environment Symposium (ILES IX). International
778 Conference of Agricultural Engineering-CIGR-AgEng 2012: Agriculture and Engineering
779 for a Healthier Life, Valencia, Spain, 8-12 July 2012, 2012. CIGR-EurAgEng, C-0476.

780 Nahm, K. H. 2003. Current Pollution and Odor Control Technologies for Poultry Production.
781 Avian and Poultry Biology Reviews, 14, 151-174.

782 Natural Resources Wales, 2020. Ammonia and nitrogen assessments for farm developments
783 that require an environmental permit or planning permission Natural Resources Wales.
784 Cambria House, 29 Newport Road, Cardiff, CF24 0TP

785 Ndegwa, P.M., Hristov, A.N., Arogo, J., Sheffield, R.E., 2008. A review of ammonia emission
786 mitigation techniques for concentrated animal feeding operations. Biosyst. Eng. 100,
787 453–469. <https://doi.org/10.1016/j.biosystemseng.2008.05.010>

788 NPWS, 2009. Appropriate Assessment of Plans and Projects in Ireland - Guidance for Planning
789 Authorities. National Parks and Wildlife Service, Dublin, Ireland.

790 Pedersen, S. & Sällvik, K. 2002. Climatization of Animal Houses - Heat and Moisture production
791 at animal and house level 4th report of CIGR working group. Research Centre Bygholm,
792 Danish Insitute of Agricultural Sciences, Horsens, Denmark.

793 Pitcairn, C.E.R., Skiba, U.M., Sutton, M.A., Fowler, D., Munro, R., Kennedy, V., 2002. Defining the
794 spatial impacts of poultry farm ammonia emissions on species composition of adjacent
795 woodland groundflora using Ellenberg Nitrogen Index, nitrous oxide and nitric oxide
796 emissions and foliar nitrogen as marker variables. *Environmental Pollution*, 119, 9–21.

797 R Core Team 2013. R: A language and environment for statistical computing, Vienna, Austria, R
798 Foundation for Statistical Computing.

799 Rinnan, Å., Nørgaard, L., van den Berg, F., Thygesen, J., Bro, R. and Engelsen, S.B., 2009. Data
800 pre-processing. *Infrared spectroscopy for food quality analysis and control*, pp.29-50.

801 Roberts, S. A., Xin, H., Kerr, B.J., Russell, J.R., Bregendahl, K. 2007. Effects of Dietary Fiber and
802 Reduced Crude Protein on Ammonia Emission from Laying-Hen Manure. *Poultry Science*
803 Association Inc.

804 Ruxton, G.D. and Neuhäuser, M., 2010. When should we use one-tailed hypothesis
805 testing?. *Methods in Ecology and Evolution*, 1(2), pp.114-117.

806 Seedorf, J., Hartung, J., Schröder, M., Linkert, K. H., Pedersen, S., Takai, H., Johnsen, J. O., Metz,
807 J. H. M., Groot Koerkamp, P. W. G., Uenk, G. H., Phillips, V. R., Holden, M. R., Sneath, R.
808 W., Short, J. L. L., White, R. P. & Wathes, C. M. 1998. A Survey of Ventilation Rates in
809 Livestock Buildings in Northern Europe. *Journal of Agricultural Engineering Research*, 70,
810 39-47.

811 Singles, R., Sutton, M.A., Weston, K.J., 1998. A multi-layer model to describe the atmospheric
812 transport and deposition of ammonia in Great Britain. *Atmospheric Environment*. 32,
813 393–399.

814 Starmans, D. A. J. & Van Der Hoek, K. W. 2007. Ammonia: The case of the Netherlands.
815 Wageningen Academic Publishers, Wageningen, The Netherlands.

816 Sutton, M. A. 2007. Report of site visit 16 January 2007 to Moninea Bog, Special Area of
817 Conservation, Northern Ireland, including results from foliar bioassay determinations
818 and subsequent ammonia monitoring. Centre for Ecology and Hydrology, Edinburgh,
819 Scotland.

820 Sutton, M., Leith, I., Bealey, W., Van Dijk, N. & Tang, Y. 2011. 3.6 Moninea Bog - Case study of
821 atmospheric ammonia impacts on a Special Area of Conservation. Nitrogen deposition
822 and Natura 2000, 58.

823 Tang, Y. S., Braban, C. F., Dragosits, U., Dore, A. J., Simmons, I., Van Dijk, N., Poskitt, J., Dos Santos
824 Pereira, G., Keenan, P. O., Conolly, C., Vincent, K., Smith, R. I., Heal, M. R. & Sutton, M.
825 A. 2018. Drivers for spatial, temporal and long-term trends in atmospheric ammonia and
826 ammonium in the UK. *Atmos. Chem. Phys.*, 18, 705-733.

827 Twigg, M. M., Braban, C. F., Anderson, M., Berkhout, S., Cowan, N., Crunaire, S., Dammers, E.,
828 Gaudion, V., Gros, V., Haaima, M., Häni, C., John, L., Jones, M. R., Kamps, B., Kentisbeer,
829 J., Kupper, T., Leeson, S. R., Leuenberger, D., Luettschwager, N., Makkonen, U., Martin,
830 N., Missler, D., Mounsor, D., Neftel, A., Nelson, C., Oudwater, R., Petit, J. E., Redon, N.,
831 Sintermann, J., Stephens, A., Zijlmans, R. & Niederhauser, B. 2018. Evaluation study of
832 the suitability of instrumentation to measure ambient NH₃ concentrations under field
833 conditions. Natural Environment Research Council. United Kingdom.

834 Tyndall, J. 2008. The use of vegetative environmental buffers for livestock and poultry odor
835 management. *Natural Resource Ecology and Management*, 5, 21-26.

836 Ulman, R., Jaňour, Z., Šeděnková, H., Drbohlav, J., 2005. The physical modelling of gas dispersion
837 in topographically complicated terrain. *EACWE* 4 328.

838 United Nations Economic Commission for Europe 2007. Report on the Workshop on Atmospheric
839 Ammonia: Detecting Emission Changes and Environmental Impacts. United Nations
840 Economic Commission for Europe. Geneva, Switzerland.

841 Van Dijk, N. (2019). Long-Term Impacts of Nitrogen Deposition & Evidence of Recovery: Whim
842 Bog and Moninea Bog. IUCN UK Peatland Conference, Belfast, 3 October 2019.

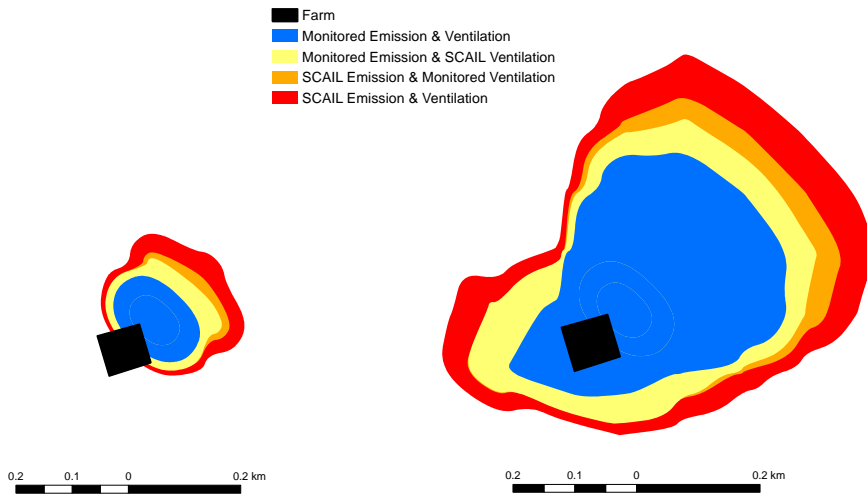
843 Wathes, C., Jones, C. & Webster, A. 1983. Ventilation, air hygiene and animal health. Veterinary
844 Record, 113, 554-559.

845 Wilkins, K., Aherne, J. & Bleasdale, A. 2016. Vegetation community change points suggest that
846 critical loads of nutrient nitrogen may be too high. Atmospheric Environment, 146, 324-
847 331.

848 Zhao, Y., Xin, H., Shepherd, T., Hayes, M., Stinn, J. & Li, H. 2013. Thermal Environment, Ammonia
849 Concentrations, and Ammonia Emissions of Aviary Houses with White Laying Hens.
850 Transactions of the ASABE, 56, 1145.

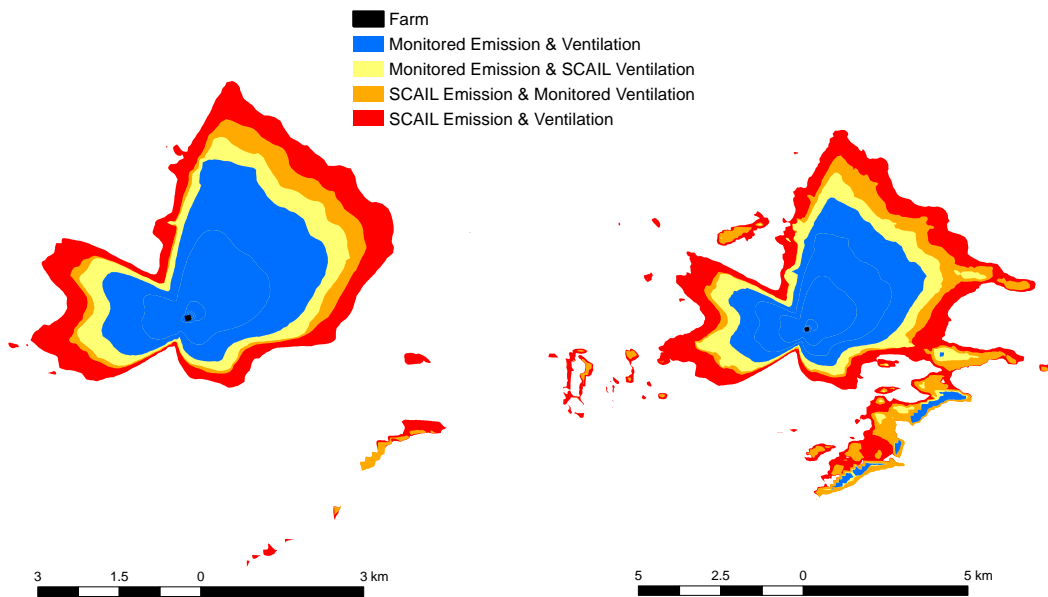
851

852 **8. Appendixes**



854 **Appendix 1. Exceedance of critical levels from contributions of laying hen housing alone for 3**
855 **$\mu\text{g NH}_3 \text{ m}^{-3}$ (Left) and 1 $\mu\text{g NH}_3 \text{ m}^{-3}$ (Right).**

856



858 **Appendix 2. Where modelled extent of presumed *de minimis* values for dry deposition (0.3 kg**
859 **$\text{N ha}^{-1} \text{ year}^{-1}$) from laying hen housing occurs when deposited over other (left) and woodland**
860 **(right) vegetation.**