Sniffer ER26: Model validation using monitored data from Scottish poultry farms

March / 2014

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SCAIL-Agriculture

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1. Introduction

This short report outlines the bespoke monitoring conducted for the validation of the SCAIL tool in order to better assess that the tool provides realistic yet conservative results.

Two farm sites were selected for the validation monitoring based on a detailed review including site visits to 6 candidate sites. These sites were selected based on the following criteria:

- *Egg layer facilities (to minimise potential variations in emission patterns associated with broiler production)*
- *Located in Central Scotland;*
- *Approximately 40,000 birds;*
- *Situated in a reasonably flat and open area and therefore suitable for collecting on-site meteorological data;*
- *Not located in close proximity to other similar sized agricultural installations to minimise background concentrations; and*
- *Livestock are likely to be present for the majority of a 3-month monitoring period.*

In addition, continuous measurements of ammonia and airborne particulate matter were conducted at one of the identified farm sites. This site had to meet the following additional criteria:

- *A location was identified within approximately 150m of the farm for the installation of continuous monitoring equipment;*
- *This location should be over undisturbed and open land from the farm;*
- *It should be possible to install mains (240 V AC) power to the location; and*
- *It should be possible to exclude livestock from the location.*

Annotated maps of the selected farm sites are shown as follows:

Whitelees Farm, South Lanarkshire – selected for continuous monitoring (Figure 1)

Glendevon Farm, Fife (Figure 2).

Table 1 provides summary information for each of the farms and highlights the pros and cons of each of the locations.

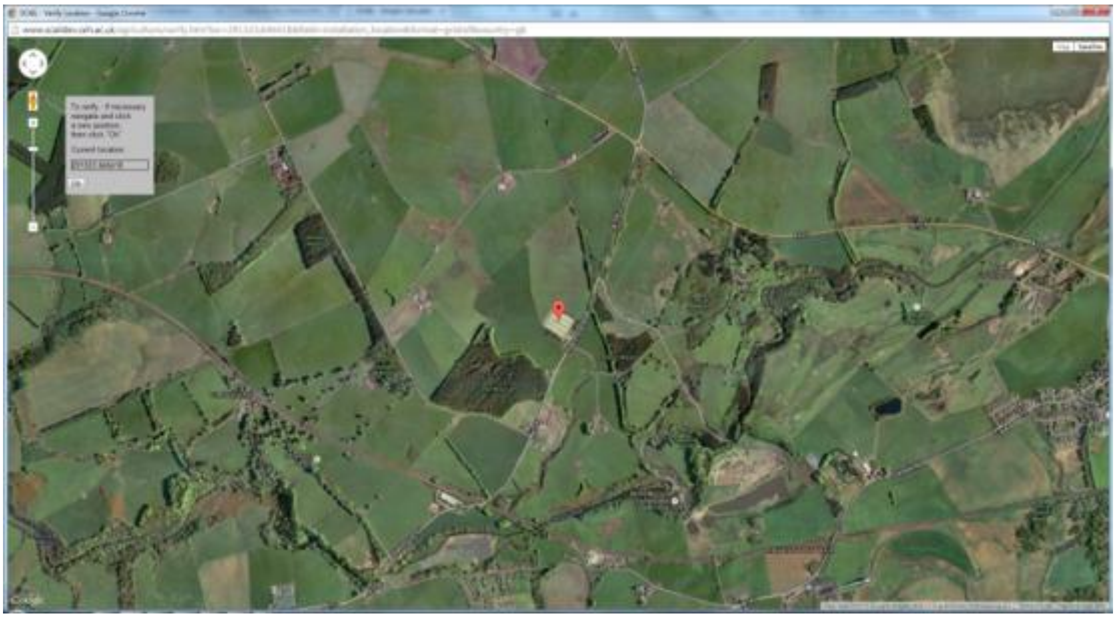


Figure 1: Whitelees Farm as shown in the "verify location" window of SCAIL-Agriculture

Figure 2: Glendevon Farm as shown in the "verify location" window of SCAIL-Agriculture

Table 1: Summary of information for the farm sites.

Farm (location)	# birds	Age (wks)	Pros	Cons	Site Type
Whitelees (55.699066, -3.730781)	37k (not Permitted) Layers	38	Good clear NE fetch for measurements; clean source area away from towns and main roads;	Cows and sheep in fields to N and W of farm.	Intensive monitoring.
Glendevon (56.052808, -3.490906)	45k Layers	<40	Good fetch; N and south; no significant animal stocking in fields in NE transect Residential house on NE edge of site which may be suitable for PM measurements	Busy B-road between farm and NE transect area: therefore not possible to put power in.	Passive monitoring.

2. Methodology

2.1. Meteorological measurements

Meteorological measurements were conducted at each of the two farm sites with automatic weather stations, equipped with dataloggers, details of the start and end times of the measurements and the height of the anemometers are included in Table 2. The meteorological measurements were recorded at a time resolution of 30 minutes and integrated to provide hourly values for processing for inclusion in the model evaluation. Table 3 lists the meteorological instruments that were deployed and the success of the measurements, noting that Solar Radiation data were not successfully recorded for Whitelees farm and that surface moisture was not recorded at Glendevon farm. It should be noted that estimates of cloud cover that are required for the modelling were derived from the solar radiation data using a reversion of the methods described in Thomson (2000) for determining surface fluxes from cloud cover data. A comparison between the calculated cloud cover and observations of cloud cover taken on the sites confirmed that this was a reliable methodology.

Table 2: Start and end times for the meteorological measurements Whitelees and Glendevon Farms and details of the anemometer height.

Run	Start (GMT)	End (GMT)	Anemometer height
Whitelees Farm	14/08/2013 12:30	04/11/2013 10:00	1.7 m
Glendevon Farm	24/07/2013 13:00	08/11/2013 10:30	7.13m

Table 3: Meteorological instruments deployed at Whitelees and Glendevon Farms.

Instrument	Parameter	Unit	Operation
Whitelees Farm			
A100R cup anemometer	Wind speed	$m\ s^{-1}$	OK (95%)
W200P windvane	Wind direction	^oN	OK (100 %)
SKP Skye pyranometer	Total solar radiation	$W\ m^{-2}$	Failed
Cassella tipping bucket	Rainfall	mm	OK (100%)
Campbell wetness grid	Surface moisture	%	OK (100%)
Vaisala HMP50 Relative humidity/T probe	Relative humidity	%	OK (100%)
Vaisala HMP50 Relative humidity/T probe	Air temperature	^oC	OK (100%)
Glendevon Farm			
A100R cup anemometer	Wind speed	$m\ s^{-1}$	OK (95%)
W200P windvane	Wind direction	^oN	OK (100%)
SKP Skye pyranometer	Total solar radiation	$W\ m^{-2}$	OK (100%)
Campbell wetness grid	Surface moisture	%	Failed
Rotronics Relative humidity/T probe	Relative humidity	%	OK (100 %)
Rotronics Relative humidity/T probe	Air temperature	^oC	OK (100%)
Type-E thermocouple	Air temperature	^oC	OK (used a primary data source with gapfilling by the Rotronics)

2.2. Ammonia Sampling

Nine ammonia monitoring locations were positioned around the Whitelees and Glendevon Poultry farms, within a 1km radius to provide information on the spatial concentration field (Figure 3 and Figure 4).

Figure 3: Google earth map of the Whitelees Poultry Farm study area, showing the locations of ammonia monitoring sites. White 1 is also the location of the meteorological and intensive (continuous) measurement site.

Figure 4: Google earth map of the Glendevon Farm study area, showing the locations of ammonia monitoring sites.

The measurement location closest to Whitelees farm (White1) was also the intensive (continuous) measurement site, positioned on the NE edge of the farm, about 55 m away from the buildings and 114 m from the centre of the farm. At this site, the following instruments and measurements were deployed (see Figure 5):

- *Meteorological station: wind direction, wind speed, temperature/humidity, solar flux, rainfall*
- *ALPHA: monthly NH_3 (one of 9 sites to provide spatial NH_3 concentration field)*
- *AiRRmonia: continuous NH_3 (measurement frequency = 1 minute, response resolution 15-30 minutes)*
- *DPAS-MANDE 2-weeky NH_3*
- *DELTA: 2-weekly NH_3*
- *ALPHA: 2 weekly NH_3*

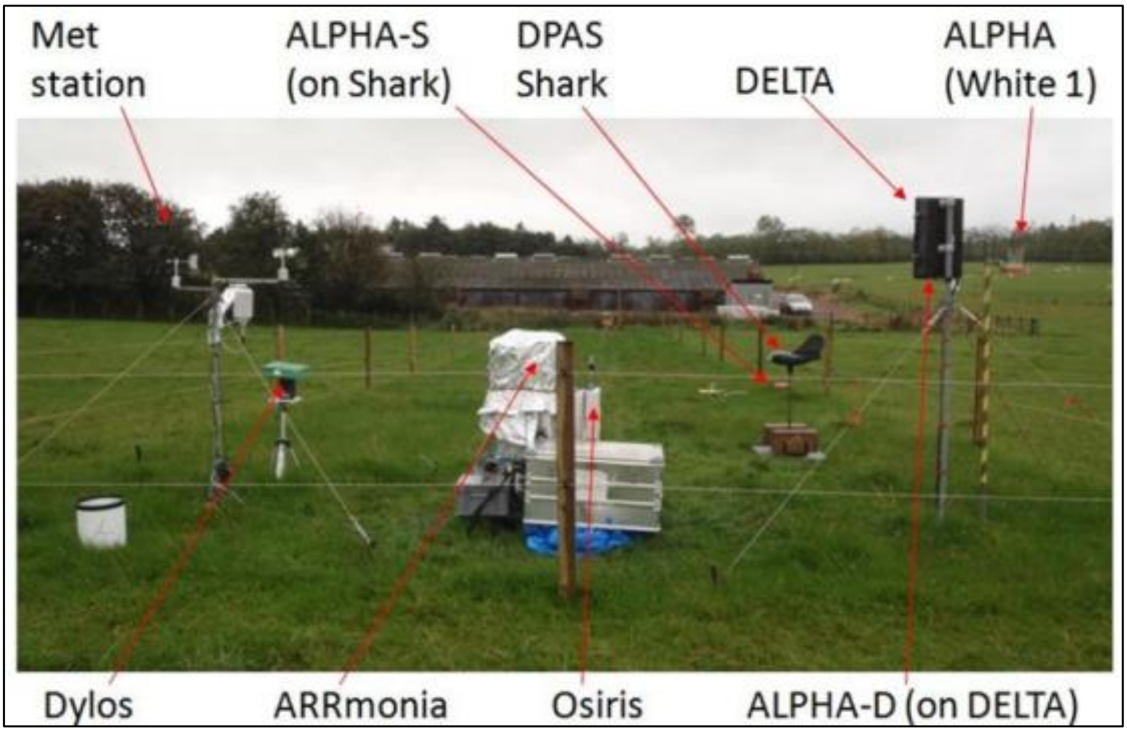


Figure 5: Whitelees Poultry Farm intensive measurement site (White 1) positioned approx. 55 m NE of the farm. Note that DPAS data are not part of this work.

2.2.1. Alpha Samplers

Atmospheric NH_3 concentrations were monitored using the CEH ALPHA (Adapted Low-cost Passive High Absorption) samplers (Tang *et al.* 2001, Puchalski *et al.* 2011). The ALPHA sampler (Figure 6) is widely used for ammonia measurements, *e.g.* in the UK National Ammonia Monitoring Network[1] (NAMN) and for assessments around intensive livestock farms (*e.g.* Tang *et al.* 2005, 2006).

[1] NAMN: http://pollutantdeposition.defra.gov.uk/networks

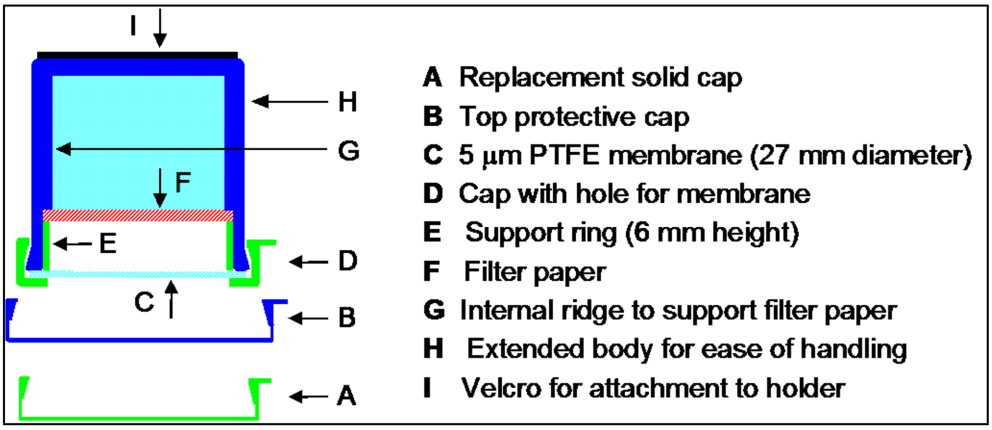


Figure 6: Outline diagram of a single ALPHA Sampler.

Triplicate samplers were attached to a holder at a sampling height of approx. 1.5 m above ground, which is the standard monitoring height used in the National Ammonia Monitoring Network and gives a reasonable surface concentration. Replicated sampling provides an estimate of measurement precision.

Monitoring was made on an approximately monthly frequency, using continuous time- integrated sampling over each period (see Table 4). A total of 4 sets of measurements were made over the period 6th August to 4th November 2013 for Whitelees and between the 24th July – 8th November 2013 at Glendevon. The ammonia samplers were prepared and analysed by CEH according to standard protocols developed at CEH (Tang *et al.* 2001). The changeover of samples was carried out by CEH personnel.

Table 4: Start and end times for the ammonia alpha samplers at Whitelees and Glendevon Farms.

Run	Start (GMT)	End (GMT)	Duration (days)
Whitelees Farm			
Run 1	06/08/2013 13:00	29/08/2013 12:00	23.0
Run 2	05/09/2013 12:00	02/10/2013 12:00	27.0
Run 3	02/10/2013 12:00	14/10/2013 12:00	12.0
Run 4	21/10/2013 13:00	04/11/2013 12:00	14.0
Glendevon Farm			
Run 1	24/07/2013 13:00	22/08/2013 15:00	29.1
Run 2	22/08/2013 15:00	25/09/2013 12:00	33.9
Run 3	25/09/2013 12:00	10/10/2013 12:00	15.0
Run 4	10/10/2013 12:00	08/11/2013 11:00	29.0

2.2.2. Diffusion Tubes (DT)

Diffusion tubes (7.1 cm Palmes-type) were used to measure NH_3 inside the poultry buildings as detailed in Table 5. The tubes are made of opaque Teflon, 7.1 cm long and 1 cm diameter. Two acidified stainless steel grids (impregnated with 35ul of 1 % m/v H_2SO_4), which serve to capture the ammonia, are held under a plastic cap and this end is placed uppermost. The other end is open and this end is placed facing the ground. During transport, the open end is capped; the cap is removed to start sampling and replaced to end sampling.

Table 5: Start and end times for the diffusion tube samplers used within the farm buildings.

Run	Shed	Start (GMT)	End (GMT)	Duration (hours)
Glendevon				
Run 1	2	05/11/2013 12:05	07/11/2013 11:25	47.3
Run 2	3	05/11/2013 12:00	07/11/2013 11:00	47.0
Run 3	4	05/11/2013 11:55	07/11/2013 11:20	47.4
Run 4	5	05/11/2013 11:50	07/11/2013 11:05	47.3
Whitelees				
Run 1	3	11/10/2013 10:50	14/10/2013 11:02	72.2
Run 2	4	11/10/2013 11:00	14/10/2013 11:05	72.1
Run 3	5	11/10/2013 11:05	14/10/2013 11:08	72.1
Run 4	6	11/10/2013 11:12	14/10/2013 11:09	72.0

2.2.3. Chemical analysis of samples and blanks

The ALPHA samplers and diffusion tubes were analysed on the AMFIA (Ammonia Flow Injection Analysis) system at CEH Edinburgh. The samples were first extracted in deionised water, and then analysed for ammonium, against a series of ammonium standards and quality controls. Parallel analysis of lab and field blank (unexposed) samples was used to determine the amounts of ammonium derived from ammonia in the atmosphere during storage.

2.2.4. Calculation of ammonia concentrations from ALPHA samplers

Based on the amount of ammonium in the sample extracts and the exposure periods, air NH_3 concentrations were calculated initially according to the theoretical sampling rate of the ALPHA sampler for ammonia. The information from the recording cards and from the chemical analyses was incorporated into an EXCEL spreadsheet for each site for calculating NH_3 concentrations, and providing supporting information.

Based on the results from the ten intercomparison sites in the UK between ALPHA and the reference DELTA method (Sutton *et al.* 2001), the appropriate calibration were applied to the ammonia data. This is necessary because the real sampling rate is slightly lower than the theoretical derived rate, since the laminar boundary layer at the sampler inlet imposes an additional resistance to gas diffusion, which is not taken into account in the theoretically derived rate.

2.2.5. Calculation of ammonia concentrations from Diffusion tubes

Based on the amount of ammonium in the sample extracts and the exposure periods, air NH_3 concentrations were calculated from the derived sampling rate of the diffusion tubes for ammonia.

2.2.6. Continuous NH_3 measurement – AiRRmonia

AiRRmonia (Mechatronics, NL: Figure 7) is an automated ammonia analyser providing continuous ammonia measurements in the field. The analyser comprises a membrane sampler for quantitative sampling of gas-phase ammonia, followed by online measurement of NH_3 concentrations.

Diffusion of NH_3 from the air stream occurs across a 0.22 µm pore size Teflon membrane into a counter flow of deionised water. At pH 7 the NH_3 converts back to NH_4 and is then transported to the detector block below. In the detector block, aqueous sample from sampling block is mixed with a carrier flow of deionised water to which an alkali (NaOH) is added. This converts all NH_4 to NH_3 in solution around pH 12. At this pH, NH_3 is the only small molecule in solution that will readily diffuse across a 0.22 µm pore size teflon membrane. The sample is passed one side of a membrane with NH_3 passing over into a counter flow of deionised water. At pH 7 the NH_3 converts back to NH_4 and the ion concentration is then analysed by conductivity. The air sampling rate is 1 l min^{-1} with measurements recorded every minute. Data was then averaged over 10 minute periods. The AiRRmonia has a limit of detection of ~0.1 µg.m^{-3}. Calibration of the analyser was carried out before and during deployment using 50 and 500 ppb NH_4 standard solutions.

Figure 7: AiRRmonia automated ammonia analyser (Mechatronics, NL)

2.2.7. DELTA and ALPHA measurements

The DEnuder for Long-Term Atmospheric (DELTA) system (Sutton *et al.* 2001) was deployed at the “White 1” intensive site to provide a check on the calibration of the ALPHA sampler. Citric acid coated denuders (15 cm in length) were used to capture NH_3 and two denuders in series were used to establish that all the NH_3 is captured. The volume of gas sampled was measured on a high sensitivity gas meter.

2.3. Odour monitoring

2.3.1. Odour concentrations in building exhausts

Samples were collected by Silsoe Odours from within buildings at 6 locations per farm per visit. Samples were collected using Nalphan NA sample bags through FEP sampling tubes. Sample bags were fitted in rigid "barrels" which were partially evacuated to provide the vacuum to draw air along the sample tube into the bags (lung principle) (see Figure 8). The vacuum was generated by portable 12v battery electric pumps.

Odour measurements were made on the samples using dynamic dilution olfactometry by Silsoe Odours to the standards defined in their UKAS accreditation (Testing Laboratory No. 0609). Odour concentrations were measured according to the BSEN13725:2003 “Air quality – Determination of odour concentration measurement by dynamic olfactometry” standard. The olfactometry measurement quantifies the concentration of odour in air samples by diluting the air sample under test with known ratios of odour-free air. The diluted samples are presented to a panel of six people to determine the odour threshold value. The threshold value is the odour concentration just perceived by 50% of the panel via statistical analysis of dilution test results. Odour concentration results are expressed in European odour units per cubic metre (OUe m^{-3}), which equates to the number of dilutions to the detection threshold. The odour concentration of an undiluted sample which is at threshold level is 1 OUe m^{-3}.

Figure 8: Monitoring odour concentrations and fan ventilation flows in the exhaust of Glendevon farm.

Odour samples collected at a single ventilation fan that operated continuously on each of three building on each site, each building was sampled twice during the time the Field Odour assessments were being performed. The numbering system for the buildings that was used in the assessment is detailed in Figure 9 and Figure 10.

Figure 9: Building identifiers for Glendevon Farm.

Figure 10: Building identifiers for Whitelees Farm.

H.2.1.1. Ammonia concentrations in building exhausts

Ammonia concentrations in the exhaust of the buildings were measured using ammonia specific Draeger tubes by sampling the air from the same bags as were used for the odour analysis detailed in the previous section. A comparison between ammonia concentrations measured directly in the vents and those from the sample bags illustrated that this method was reliable and not affected by sampling artefacts.

2.3.2. Gas flows from the building exhausts

The air speed from each fan duct sampled was measured by sampling on a grid of 12 sampling points over the plane of the duct. The 12 values were averaged then the volume flow rate calculated

All the fans on the buildings at the Glendevon site were set to operate throughout the period that emissions from the buildings were measured. The normal target temperature for the internal temperature is 21 °C. This temperature was maintained on average on the 18 September but because of a lower ambient temperature on the 25th September the internal temperature was lower at an average of 17.2 °C.

Because of the elevation of Whitelees farm and cooler weather on the 19th September the fans on these buildings were set to operate on Stage 2 throughout the monitoring period. The normal target temperature for the internal temperature is 21 °C, but this temperature was not maintained on the 19th September and the average was 17.7 °C. On the 26th September the ambient temperature was lower so to maintain an acceptable internal temperature the ventilation system was set to automatic. The average internal temperature was maintained at an average of 21.3 °C.

2.3.3. Ambient odour analysis

Ambient odours were measured by a panel of 3 “sniffers”. The “sniffers” are all members of the Silsoe odour panel and are subject to the standardisation checks and analysis required by BSEN13725:2003 (although it should be noted that the analysis by the field panellists does not fall within the UKAS accreditation of Silsoe odours).

The assessors were instructed to have stopped eating or smoking at least 30 minutes before the measurement. At each measuring point the measuring procedure lasts about 15 minutes and comprises the registration of the odour frequency, the assessment of the odour intensity and description of the odour as well as a short description of the wind and weather conditions. The assessors test the ambient air by inhaling at 10 seconds intervals, which gives 60 samples in ten minutes. Following the recognition of the odour the panelist is asked to assess the odour intensity on the 0 to 6 scale. 1 on the scale would be an odour but not recognizable, 2 is a faint recognizable odour and 3 is a distinct odour that, if offensive, might cause annoyance. All the responses are recorded on the data collection form (Figure 11).

The "sniffers" recorded odour quality (the type of odour – in this case they were only instructed to report on "poultry odour" or "no odour") and intensities (on a scale of 0 – 6) at 10 second intervals over a period of 10 minutes. From this information the frequency of occurrence of an odour being detected and average intensity of the odour when detected were determined. The 10 minutes duration of a single measurement provides an 80% reliability that the sample is representative of the odour situation of a particular hour. The percentage of time a given descriptor was used and the mean intensity of the odours with that description were calculated.

Odour concentrations were determined from a calibration curve established from the olfactometer between odour intensity and concentration at various downwind locations.

Locations used for the odour assessment are shown in Figure 12 and Figure 13.

SILSOE ODOURS Ltd
Building 42, Wrest Park, Silsoe,
Bedfordshire, Tel & fax +44 (0)1525 860222

Data collection form for Field Measurements

		Date		WIND direction	
Measurement point		Panel member		wind strength	
Start of measurement		End of measurement			

wind strength	
0	calm
1	smoke drifts
2	leaves rustle
3	leaves and twigs move
4	dust & paper lifte
5	branches move

														Quality totals	intensity total
1 minute							2 minute								
						quality									
						intensity									
3 minute							4 minute								
						quality									
						intensity									
5 minute							6 minute								
						quality									
						intensity									
7 minute							8 minute								
						quality									
						intensity									
9 minute							10 minute								
						quality									
						intensity									

Odour Qualities

N	no odour
A	poultry
B	cattle
C	sheep
D	
E	
F	

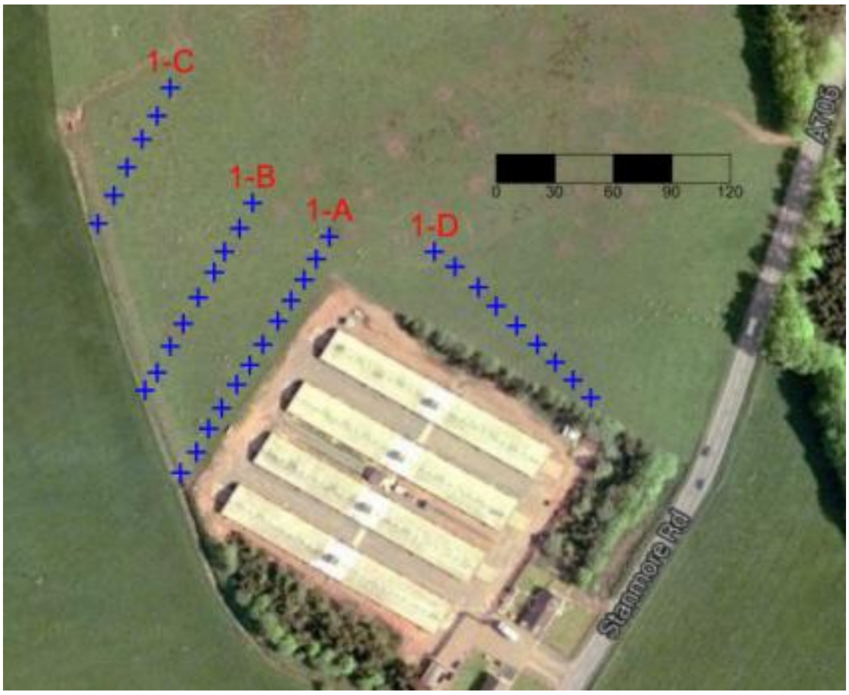
Odour intensity

0	no odour	
1	Very faint	(inkling)
2	Faint	(certain)
3	Distinct	
4	Strong	
5	Very Strong	
6	Extremely Strong	

it is not a question of a sensitive response to odours but clear recognition of the odour, odour quality, and intensity

Figure 11: The odour assessor's data collection form

19th September 2013



26th September2013

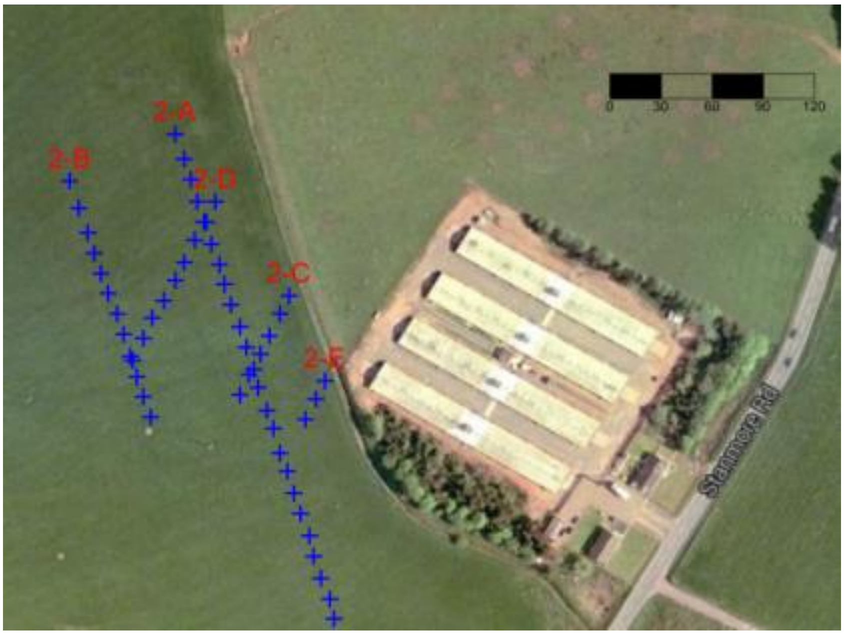


Figure 12: Locations of the odour sampling positions at Whitelees farm. Scale bar shown in metres.

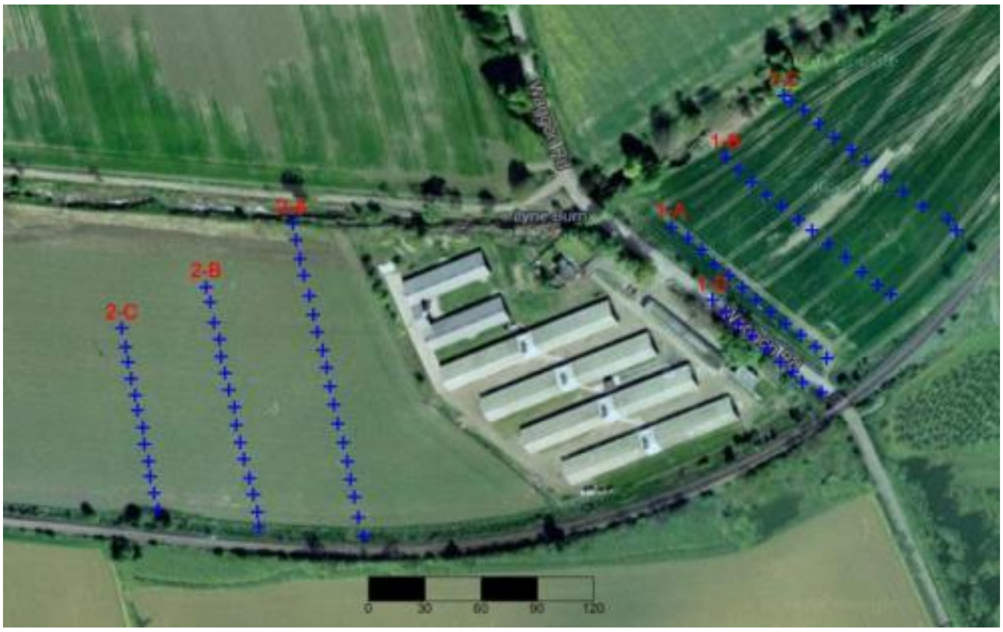


Figure 13: Locations of the odour sampling positions at Glendevon farm. Scale bar shown in metres.

2.4. PM_{10} measurements

A Turnkey Osiris monitor was used for the ambient particle measurements at Whitelees farm (site White 1). This monitor is designed to be used for both fixed location and mobile monitoring and uses near forward light scattering (5^o) to count and size particles, drawn into the photocell by a diaphragm pump operating at 0.6 l $minute^{-1}$. As total airborne particle concentrations were less than 6 mg m^{-3}, the monitor was able to size particles into 4 fractions (note only the PM_{10} data are reported herein):

- *Total Suspended Particulate (TSP);*
- *Particles of size $\leq$10 micrometres (PM_{10});*
- *Particles of size $\leq$2.5 micrometres ($PM_{2.5}$); and*
- *Particles of size $\leq$1 micrometres (PM_1).*

The mass of particles in each class was recorded separately on the internal datalogger. The Osiris was factory calibrated for each particle size range with the calibration being certified by the manufacturer on the 9th of May 2013. The sampler also has an auto-zero facility, where filtered air is passed over the instrument's optics to confirm the zero point of the calibration. The OSIRIS was deployed at site "White 1" (see Figure 3 and Figure 5) in a protective enclosure with a heated air inlet to prevent interference from airborne water droplets (see Figure 14).

It should be noted that this instrument provides an indicative estimate of particle concentrations and is not an equivalent to gravimetric sampling required to demonstrate compliance with the CAFE directive.

Figure 14: Osiris monitor deployed in the field in a weather proof enclosure at Whitelees farm (site White 1).

A DUSTTRAK II Aerosol Monitor (Model 8532) was used to measure particulate concentrations within the vents of the animal houses. This instrument is handheld and battery-operated with an internal data-logger. It uses a light-scattering laser photometer to provide real-time aerosol mass readings and uses a sheath air system that isolates the aerosol in the optics chamber to keep the optics clean for improved reliability and low maintenance. It has been designed for clean office settings as well as harsh industrial workplaces, construction and environmental sites, and other outdoor applications. The instrument can measure aerosol concentrations corresponding to PM_1, $PM_{2.5}$, Respirable, or PM_{10} size fractions in the concentration range 0.001 to 150 mg m^{-3} and was deployed with a size selective inlet to enable the recording of PM_{10} concentrations (see Figure 15).

Figure 15: DUSTTRAK II ambient particle monitor shown with the PM_{10} size selective inlet in place.

2.5. Model validation methodology

The methodologies for the validation of the tool and the various datasets were discussed in the Validation Plan (Theobald, 2011). The validation process consisted of three key stages:

- *Model performance analysis using best estimates of model inputs;*
- *Estimation of model prediction uncertainty due to uncertainty in model input data;*
- *Estimation of model prediction uncertainty due to the simplification of model input data.*

The SCAIL-Agriculture tool was run using the best estimates of model input data and the default (nearest) SCAIL-Agriculture regional meteorological station (for both these farms the station was Edinburgh Gogorbank). In addition the on-site meteorological data were formatted for direct use in the model as a comparison with the regional meteorological data. These best estimates of model inputs were either the real values (where available) or based on expert judgement. The predicted concentrations (C_p) were then compared with the measured values (C_o) and the four following performance indicators were calculated for each dataset:

- *Fractional bias;*
- *Geometric mean bias;*
- *Normalised mean square error;*
- *Geometric variance.*

In addition we used a fifth metric, the fraction of model predictions within a factor of two of the observations (FAC2).

Chang and Hanna (2004) suggest ranges for five of the performance measure values that indicate acceptable model performance. The ranges suggested are:

- *-0.3<|FB|<0.3;*
- *0.7<MG<1.3;*
- *NMSE<1.5;*
- *VG<4; and*
- *FAC2>50%.*

Recent work on model performance evaluation by Hanna and Chang (2010) has recognised that, due to stochastic and turbulent processes, even an acceptable model may not meet all acceptability criteria for all experiments. As a result, they propose that an acceptable model is one that meets the criteria for at least half of the performance tests.

3. Monitoring Results

3.1. Meteorological measurements

Wind roses are shown in Figure 16 and Figure 17 for Glendevon and Whitelees farms respectively. These illustrate the dominance of winds from the west at Glendevon Farm and from the south-west at Whitelees Farm over the monitoring period.

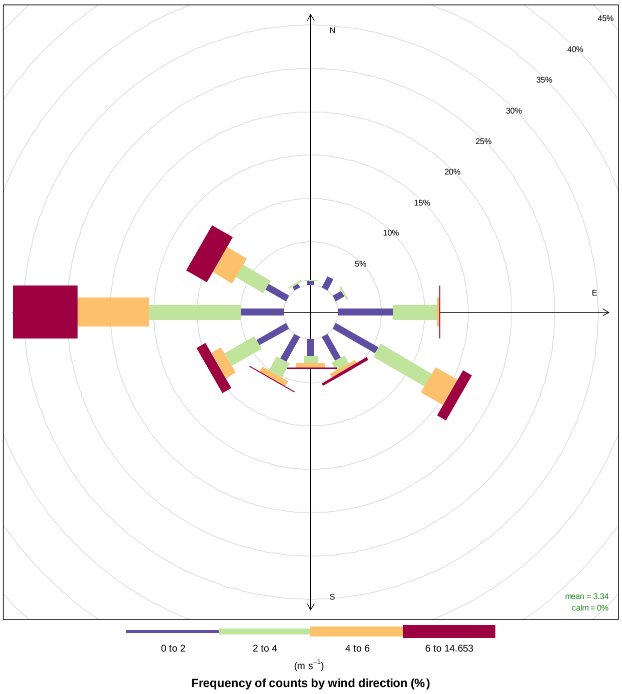


Figure 16: Wind rose determined from the on-site meteorological station at Glendevon farm

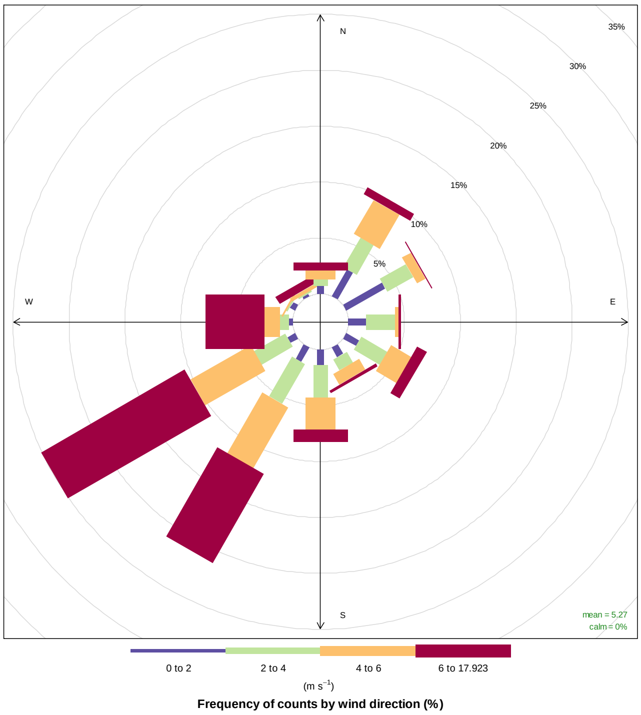


Figure 17: Wind rose determined from the on-site meteorological station at Whitelees farm

3.2. Source term measurements

3.2.1. Odour and ammonia concentrations and building temperature

Ammonia concentrations and odour concentrations were determined from samples collected in the vents of the farm buildings using Naptan NA sampling bags. Ammonia and odour concentrations and air temperatures for Glendevon farm are shown in Table 6 and for Whitelees farm are shown in Table 7. Ammonia concentrations in the vents of the buildings at Glendevon farm were similar to measurements collected by the site operators for ensuring compliance with Occupational Exposure Levels (data not shown). Overall there was a reasonable agreement between the concentrations collected on each of the visits to the site. There were generally higher ammonia and odour concentrations recorded from Whitelees farm than from Glendevon farm.

Ammonia concentrations were also measured in the farm buildings using Palmes diffusion tubes over periods of several days. On analysis of the results it would appear that these tubes may have been saturated and hence actual concentrations may have been under-represented. Nevertheless the concentrations recorded were similar to, if not higher than, the short term measurements collected at the building vents (see Table 8).

Table 6: Odour and ammonia results for Glendevon farm.

Date / Time (GMT)	Building	Odour concentration OUe m^{-3}	Ammonia concentration mg m^{-3} (ppm)	Temperature at fan outlet °C
18/09/13				
11:54	2	142	14 (20)	21.6
12:16	3	124	14 (20)	20.7
12:35	5	226	12 (18)	21.5
13:54	5	225	12 (17)	20.2
14:07	3	115	9 (13)	20.9
14:31	2	157	14 (21)	21.1
25/09/13				
12:44	2	540	10 (15)	17.8
13:02	3	200	10 (15)	18.1
13:29	5	249	12 (17)	17.5
14:04	5	256	10 (14)	17.1
14:20	3	158	7 (10)	16.3
14:33	2	183	8 (12)	16.5

Table 7: Odour and ammonia results for Whitelees farm.

Date / Time (GMT)	Building	Odour concentration OUe m^{-3}	Ammonia concentration mg m^{-3} (ppm)	Temperature at fan outlet °C
19/09/13				
09:51	1	218	11 (16)	15.1
10:15	4	307	17 (24)	17.5
10:31	8	246	19 (28)	18.6
12:27	8	347	18 (26)	19.5
12:37	4	247	16 (23)	18.3
12:54	1	218	12 (17)	17.0
26/09/13				
09:34	1	267	24 (35)	17.8
10:04	4	306	21 (31)	18.1
10:31	8	327	30 (44)	17.5
12:12	8	321	21 (31)	17.1
12:37	4	275	12 (18)	16.3
12:50	1	216	22 (32)	16.5

Table 8: Ammonia concentrations measured using Palmes tubes. Note that due to potential saturation of the filters these may be underestimates of actual values.

Run	Shed	Start (GMT)	End (GMT)	Duration (hours)
Glendevon				
Run 1	2	05/11/2013 12:05	07/11/2013 11:25	22.4
Run 2	3	05/11/2013 12:00	07/11/2013 11:00	22.9
Run 3	4	05/11/2013 11:55	07/11/2013 11:20	23.0
Run 4	5	05/11/2013 11:50	07/11/2013 11:05	22.4
Whitelees				
Run 1	3	11/10/2013 10:50	14/10/2013 11:02	15.2
Run 2	4	11/10/2013 11:00	14/10/2013 11:05	15.2
Run 3	5	11/10/2013 11:05	14/10/2013 11:08	15.2
Run 4	6	11/10/2013 11:12	14/10/2013 11:09	15.1

3.2.2. PM_{10} Concentrations and ventilation measurements

Measurements of the PM_{10} concentrations and air flows in the vents of the farm buildings are shown in Table 9 and Table 10 for Glendevon Farm and Table 11 for Whitelees Farm.

Table 9: PM_{10} concentrations and ventilation rates measured at Glendevon Farm on the 18th of September.

Date / Time (GMT)	Building	Vent	PM_{10} concentration (mg m^{-3})	Area of vent (m^2)	Speed (m/s)	Air flow (m^3/s)
11:00	3	1	0.141	0.41	1.50	0.61
11:03	3	2	0.219	0.39	0.80	0.32
11:05	3	3	0.243	0.40	4.00	1.59
11:07	3	4	0.267	0.41	3.60	1.46
11:10	3	5	0.411	0.41	3.50	1.42
11:12	3	6	0.307	0.41	2.10	0.85
11:13	3	7	0.338	0.41	3.40	1.38
11:15	3	8	0.174	0.36	5.30	1.93
11:17	3	9	0.356	0.46	0.50	0.23
11:19	3	10	0.614	0.45	2.70	1.22
11:21	3	11	0.537	0.44	2.70	1.20
11:23	3	12	0.327	0.44	4.70	2.07
11:25	3	13	0.346	0.44	4.70	2.08
11:27	3	14	0.207	0.44	2.70	1.18
11:28	3	15	0.229	0.36	4.70	1.68
11:30	3	16	0.24	0.42	2.90	1.22
13:40	5	1	0.251	0.38	5.18	1.97
13:41	5	1	0.263	0.38	5.18	1.97
13:43	5	1	0.171	0.38	5.18	1.97
14:07	3	8	0.207	0.36	5.51	2.01
14:22	2	1	0.12	0.36	3.40	1.21
14:24	2	1	0.228	0.36	3.41	1.22

Table 10: PM_{10} concentrations and ventilation rates measured at Glendevon Farm on the 25th of September.

Date / Time (GMT)	Building	Vent	PM_{10} concentration (mg m^{-3})	Area of vent (m^2)	Speed (m/s)	Air flow (m^3/s)
10:55	3	1	0.123	0.38	5.69	2.17
11:00	3	2	0.169	0.37	4.14	1.54
11:06	3	3	0.205	0.38	3.73	1.42
11:18	3	4	0.159	0.37	3.05	1.14
11:23	3	5	0.211	0.37	3.05	1.14
11:28	3	6	0.225	0.37	3.00	1.12
11:32	3	7	0.206	0.37	3.00	1.12
11:38	3	8	0.069	0.37	4.94	1.84
11:40	3	8	0.229	0.37	3.00	1.12
11:50	3	7	0.202	0.44	2.88	1.26
11:55	3	9	0.281	0.43	2.90	1.24
11:59	3	10	0.389	0.44	2.78	1.21
12:03	3	11	0.42	0.44	4.60	2.01
12:07	3	12	0.382	0.44	5.05	2.21
12:11	3	13	0.227	0.44	3.01	1.32
12:15	3	14	0.226	0.36	3.64	1.30
12:19	3	15	0.173	0.44	3.15	1.38
12:23	3	16	0.172	0.37	5.10	1.90
13:52	5	1	0.123	0.36	3.14	1.12
13:57	5	4	0.282	0.49	2.76	1.34
14:03	5	7	0.147	0.43	2.84	1.22
14:08	5	9	0.161	0.49	2.65	1.29
14:14	5	14	0.282	0.36	3.79	1.38
14:27	4	1	0.123	0.44	5.43	2.37
14:32	4	4	0.138	0.44	3.10	1.36
14:37	4	7	0.172	0.49	2.54	1.23
14:42	4	9	0.152	0.49	2.43	1.18
14:47	4	14	0.119	0.37	4.00	1.49
14:57	2	16	0.09	0.37	3.85	1.43
14:58	2	16	0.097	0.36	3.90	1.39
15:09	2	9	0.145	0.39	4.01	1.56
15:16	2	5	0.207	0.37	3.06	1.14
15:22	2	1	0.156	0.36	4.70	1.68
15:28	1	2	0.098	0.37	4.94	1.84

Table 11: PM_{10} concentrations and ventilation rates measured at Whitelees Farm.

Date / Time (GMT)	Building	Vent	PM_{10} concentration (mg m^{-3})	Area of vent (m^2)	Speed (m/s)	Air flow (m^3/s)
19/09/2013						
09:54	3	1	0.094	0.39	5.2	2.03
10:13	3	5	0.089	0.41	5.4	2.21
10:25	4	6	0.087	0.41	5.5	2.25
10:34	4	10	0.072	0.41	5.6	2.29
10:41	4	11	0.128	0.41	2.6	1.06
10:51	4	15	0.104	0.41	3.5	1.43
11:00	3	16	0.106	0.41	3.8	1.56
11:10	3	20	0.115	0.41	3.2	1.31
11:14	1	1	0.187	0.40	4.2	1.68
26/09/2013						
09:41	1	2	0.458	0.41	5.55	2.30
09:48	1	20	0.274	0.41	3.94	1.61
09:58	4	8	0.21	0.42	6.28	2.63
10:05	2	9	0.226	0.41	4.96	2.03
10:11	2	11	0.257	0.42	4.64	1.94
10:16	4	10	0.309	0.42	2.51	1.05
10:21	4	11	0.296	0.42	4.53	1.89
10:26	4	13	0.202	0.43	4.33	1.85
10:32	3	18	0.258	0.43	4.06	1.74
10:34	3	20	0.332	0.42	5.68	2.38
10:44	3	1	0.277	0.41	3.44	1.41
10:49	3	3	0.257	0.42	5.64	2.36
11:56	5	2	0.187	0.41	3.71	1.52
12:00	5	5	0.257	0.41	3.99	1.63
12:04	6	6	0.199	0.43	4.86	2.08
12:08	6	9	0.19	0.41	4.41	1.81
12:14	6	11	0.23	0.41	4.61	1.89
12:19	6	14	0.131	0.40	4.30	1.72
12:24	5	17	0.154	0.41	3.80	1.56
12:29	5	20	0.186	0.42	4.80	2.01
12:38	7	1	0.175	0.42	4.61	1.93
12:48	8	10	0.151	0.41	5.14	2.10
12:54	8	11	0.205	0.42	5.65	2.37
13:00	7	20	0.164	0.41	4.23	1.73

3.2.3. Emission rates from the buildings

The data on ammonia, odour and PM_{10} concentrations in the vents of the buildings at Whitelees and Glendevon farms along with the ventilation rates were used to calculate emissions from each of the buildings. Where data were not measured for a particular building then these data were interpolated as the average of the available measurements from the other buildings on the site.

Emissions data for Glendevon farm are shown in Table 12 and data for Whitelees farm are shown in Table 13. Measurements of ventilation rate from individual fans and the whole site were similar on both days but there were no records of the times when each fan was operating. Consequently for Glendevon farm the farm manager left the fans switched on continuously on the 18th and 25th of September. Therefore the ventilation rate recorded in Table 12 is likely to overestimate the actual value.

Table 12: Summary of emissions data for Glendevon Farm.

Building	No. vents operating	Total air flow (m^3 / s)	Emissions (per year, assuming continuous operation)		
			PM_{10} (kg)	Odour (kOu)	NH_3 (kg)
18/09/2013 Glendevon					
1	14	21	1.51E+02	1.09E+08	8.31E+03
2	16	19	1.02E+02	9.16E+07	8.66E+03
3	16	21	1.98E+02	7.97E+07	7.59E+03
4	16	24	1.73E+02	1.25E+08	9.50E+03
5	16	32	2.20E+02	2.24E+08	1.20E+04
Sub total	78	117	8.45E+02	6.30E+08	4.61E+04
25/09/2013 Glendevon					
1	14	23	6.88E+01	1.95E+08	7.06E+03
2	16	22	9.49E+01	2.56E+08	6.60E+03
3	16	23	1.68E+02	1.30E+08	6.28E+03
4	16	24	1.03E+02	2.01E+08	7.24E+03
5	16	22	1.34E+02	1.75E+08	7.41E+03
Sub total	78	115	5.69E+02	9.57E+08	3.46E+04
Average	78	116	7.07E+02	7.93E+08	4.03E+04

Note: data in red were not measured for the specified building and were calculated from the average of measured data from the other buildings.

Table 13: Summary of emissions data for Whitelees Farm.

Building	No. vents operating	Total air flow (m^3 / s)	Emissions (per year, assuming continuous operation)		
			PM_{10} (kg)	Odour (kOu)	NH_3 (kg)
19/09/2013 Whitelees					
1	4	6.7	3.50E+01	4.62E+07	2.42E+03
2	4	7.0	2.26E+01	5.81E+07	3.39E+03
3	4	7.1	1.77E+01	5.92E+07	3.46E+03
4	4	7.0	1.68E+01	6.15E+07	3.60E+03
5	4	7.0	2.26E+01	5.81E+07	3.39E+03
6	4	7.0	2.26E+01	5.81E+07	3.39E+03
7	4	7.0	2.26E+01	5.81E+07	3.39E+03
8	4	7.0	2.02E+01	6.59E+07	4.14E+03
Sub total	32	55.9	1.80E+02	4.65E+08	2.72E+04

Building	No. vents operating	Total air flow (m^3 / s)	Emissions (per year, assuming continuous operation)		
			PM_{10} (kg)	Odour (kOu)	NH_3 (kg)
26/09/2013 Whitelees					
1	2	3.9	4.38E+01	2.98E+07	2.85E+03
2	4	7.9	5.79E+01	7.15E+07	5.50E+03
3	4	7.9	6.72E+01	7.09E+07	5.46E+03
4	4	7.4	5.71E+01	6.80E+07	3.96E+03
5	4	6.7	3.93E+01	6.05E+07	4.65E+03
6	4	7.5	4.18E+01	6.75E+07	5.19E+03
7	2	3.7	1.84E+01	3.29E+07	2.54E+03
8	2	4.5	2.36E+01	4.57E+07	3.65E+03
Sub total	26	49.5	3.49E+02	4.47E+08	3.38E+04
Average	29	52.3	2.65E+02	4.56E+08	3.05E+04

Note: data in red were not measured for the specified building and were calculated from the average of measured data from the other buildings.

3.3. Ambient measurements

3.3.1. Odour

The odour samples collected for the evaluation of the source-terms from the farm buildings were used to define the relationship between odour intensity (as defined on the 0-6 scale) and odour concentration (as determined by dynamic dilution olfactometry). The resulting calibration curves determined by fitting an exponential relationship to the data are shown in Figure 18 to Figure 21. These exponential relationships were applied to convert the odour intensities measured in the field to derive odour concentrations.

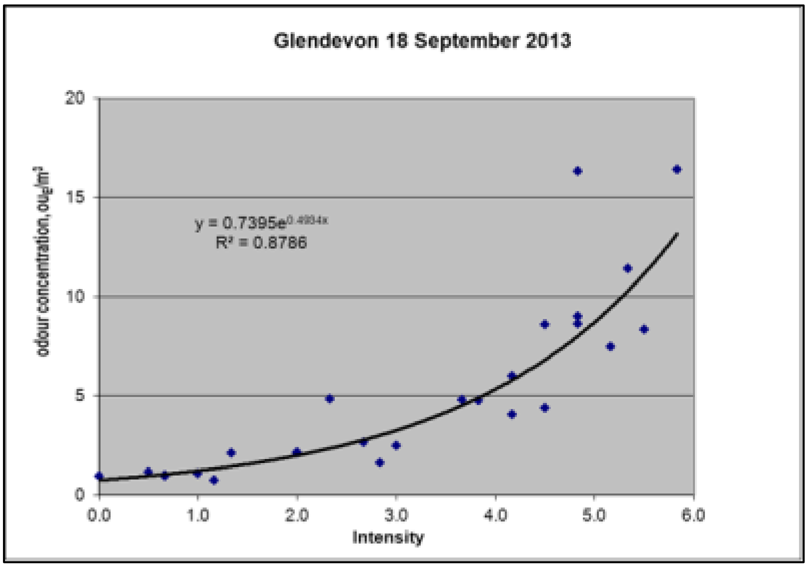


Figure 18: Odour concentration vs. Intensity for the Glendevon samples on 18th September.

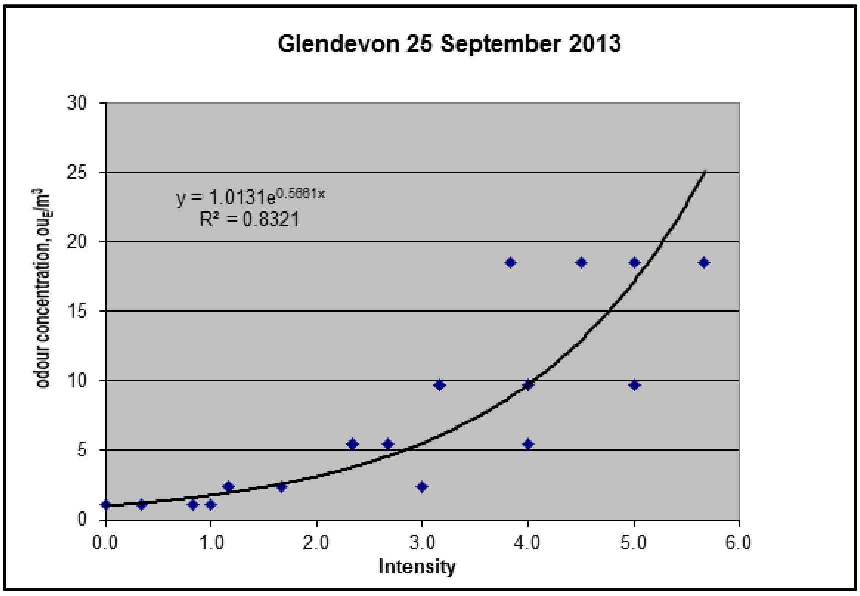


Figure 19: Odour concentration vs. Intensity for the Glendevon samples on 25th September.

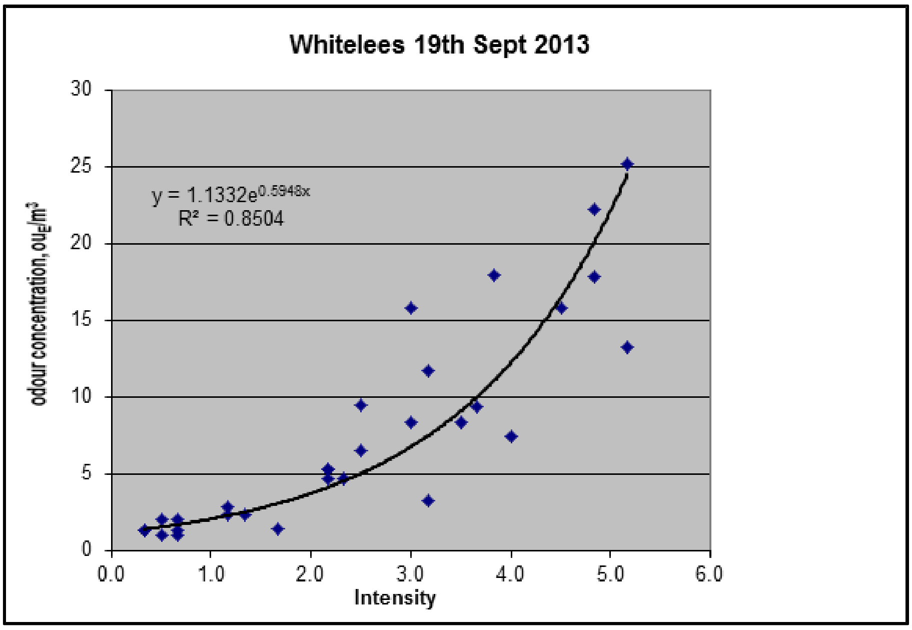


Figure 20: Odour concentration vs. Intensity for the Whitelees samples on 19th September.

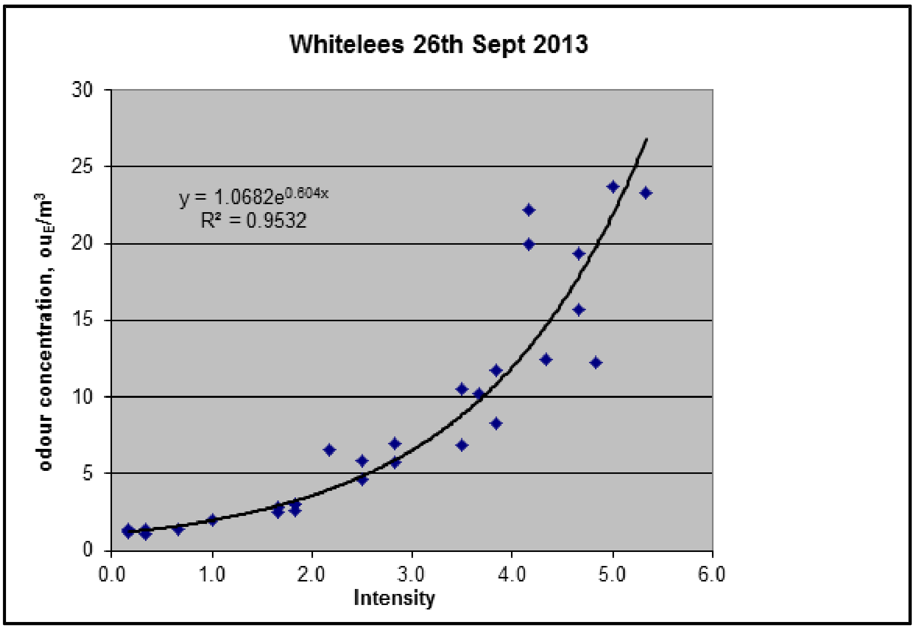


Figure 21: Odour concentration vs. Intensity for the Whitelees samples on 26th September.

A summary of the data collected by the field odour assessors is shown in Table 14 to Table 17. The "Average Conc." values shown are averaged over the time periods that an odour was experienced. In order to compare these data with the time-averaged predictions from SCAIL-Agriculture the "Average Conc." data were multiplied by the "Frequency of time" to convert the data to time-averaged values.

Table 14: Summary of odour observations at Glendevon farm on 18th September with intensity converted to odour concentration.

Transect (distance)	Time (GMT)	X-wind distance (m)	Frequency (% of time)	Mean Intensity	Average Conc. (OUe/m³)
1-D (20 m)	14:57	0	50	1.5	1.55
	14:57	10	53	2.13	2.12
	14:57	20	100	1	1.21
	15:11	30	80	2	1.98
	15:11	40	47	2.25	2.24
	15:11	50	43	1	1.21
	15:25	60	68	2.39	2.40
	15:25	70	38	2.13	2.12
	15:25	80	80	1.17	1.32
1-A (50 m)	11:24	0	48	1.31	1.41
	11:24	10	58	1.94	1.93
	11:24	20	7	1.5	1.55
	11:38	30	53	1.63	1.65
	11:38	40	45	1.74	1.74
	11:38	50	53	1.38	1.46
	11:52	60	67	1.8	1.80
	11:52	70	40	2.29	2.29
	11:52	80	10	1	1.21
	12:06	90	42	1.6	1.63
	12:06	100	17	1.6	1.63
	12:06	110	0	0	0.74
1-B (100 m)	12:21	110	17	1	1.21
	12:21	100	7	1	1.21
	12:21	90	5	1	1.21
	12:34	80	0	0	0.74
	12:34	70	25	1.67	1.69
	12:34	60	42	1.24	1.36
	13:28	50	72	1	1.21
	13:28	40	20	1.75	1.75
	13:28	30	48	1.41	1.48
	13:41	20	22	1.62	1.64
	13:41	10	23	2	1.98
	13:41	0	27	1.75	1.75
1-C (150 m)	13:58	0	15	1.11	1.28
	13:58	10	3	1	1.21
	13:58	20	2	1	1.21
	14:11	30	5	1	1.21
	14:11	40	12	1	1.21
	14:11	50	18	1	1.21
	14:24	60	2	1	1.21
	14:24	70	8	1.2	1.34
	14:24	80	0	0	0.74
	14:36	90	0	0	0.74
	14:36	100	15	1.56	1.60
	14:36	110	12	1.43	1.50

Table 15: Summary of odour observations at Whitelees farm on 19th September with intensity converted to odour concentration.

Transect (distance)	Time (GMT)	X-wind distance (m)	Frequency (% of time)	Mean Intensity	Average Conc. (OUe/m³)
1-A (20 m)	09:10	0	23	1.57	2.88
	09:10	10	33	1.45	2.68
	09:10	20	40	2.5	5.01
	09:22	30	87	1.44	2.67
	09:22	40	100	1.27	2.41
	09:22	50	95	2.47	4.92
	09:35	60	95	2.35	4.59
	09:35	70	70	1.67	3.06
	09:35	80	80	2.21	4.22
	09:49	90	67	2.15	4.07
	09:49	100	88	1.58	2.90
	09:49	110	67	1.83	3.37
1-B (50 m)	10:06	0	57	2.03	3.79
	10:06	10	93	1.39	2.59
	10:06	20	65	2.03	3.79
	10:18	30	18	1.64	3.01
	10:18	40	15	1	2.05
	10:18	50	15	1.33	2.50
	10:34	60	13	2.5	5.01
	10:34	70	22	2	3.72
	10:34	80	18	1.36	2.54
1-C (100 m)	10:48	0	7	1	2.05
	10:48	10	2	1	2.05
	10:48	20	3	2	3.72
	11:03	30	0	0	1.13
	11:03	40	0	0	1.13
	11:03	50	0	0	1.13
1-D (50 m)	12:24	0	15	1.44	2.67
	12:24	10	45	1.15	2.25
	12:24	20	48	1.48	2.73
	12:37	30	52	1.87	3.45
	12:37	40	100	1.28	2.43
	12:37	50	50	1.77	3.25
	12:50	60	27	1.63	2.99
	12:50	70	22	1	2.05
	12:50	80	27	1.56	2.87

Table 16: Summary of odour observations at Glendevon Farm on 25th September with intensity converted to odour concentration.

Transect (distance)	Time (GMT)	X-wind distance (m)	Frequency (% of time)	Mean Intensity	Average Conc. (OUe/m^3)
2-A (50 m)	12:24	0	28	1.65	2.58
	12:24	10	15	1.44	2.29
	12:24	20	10	1.5	2.37
	12:37	30	43	1.92	3.00
	12:37	40	55	1.73	2.70
	12:37	50	53	2.03	3.20
	12:50	60	73	2.34	3.81
	12:50	70	55	2.61	4.44
	12:50	80	42	2.16	3.44
	13:04	90	73	2.34	3.81
	13:04	100	58	2.49	4.15
	13:04	110	42	2.16	3.44
	13:18	120	60	2.31	3.75
	13:18	130	50	2.2	3.52
	13:18	140	12	1.86	2.90
	13:32	150	47	1.79	2.79
	13:32	160	40	1.71	2.67
	13:32	170	17	1.8	2.81
2-B (100 m)	13:49	170	32	1.74	2.71
	13:49	160	23	1.79	2.79
	13:49	150	17	1.8	2.81
	14:02	140	52	1.84	2.87
	14:02	130	30	1.72	2.68
	14:02	120	20	1.67	2.61
	14:14	110	30	1.33	2.15
	14:14	100	33	1.8	2.81
	14:14	90	3	1.5	2.37
	14:27	80	13	1.5	2.37
	14:27	70	2	1	1.78
	14:27	60	5	1	1.78
	14:40	50	0	0	1.01
	14:40	40	7	1.25	2.06
	14:40	30	0	0	1.01
2-C (150 m)	14:59	170	23	1.21	2.01
	14:59	160	33	1.55	2.44
	14:59	150	25	1.47	2.33
	15:13	140	20	1.33	2.15
	15:13	130	15	1.78	2.78
	15:13	120	10	1.33	2.15
	15:26	110	17	1.3	2.11
	15:26	100	7	1.75	2.73
	15:26	90	7	1	1.78
	15:40	80	5	1.33	2.15
	15:40	70	3	1.5	2.37
	15:40	60	0	0	1.01

Table 17: Summary of odour observations at Whitelees farm on 26th September with intensity converted to odour concentration.

Transect (distance)	Time (GMT)	X-wind distance (m)	Frequency (% of time)	Mean Intensity	Average Conc. (OUe/m³)
2-A (50 m)	08:51	0	3	1	1.95
	08:51	10	5	1	1.95
	08:51	20	5	1	1.95
	09:03	30	10	1.17	2.17
	09:03	40	10	1.33	2.39
	09:03	50	15	1.44	2.55
	09:15	60	22	1.38	2.46
	09:15	70	18	1.73	3.04
	09:15	80	23	2	3.58
	09:27	90	52	2.26	4.18
	09:27	100	58	2.54	4.95
	09:27	110	63	2.16	3.94
	09:40	120	45	2.41	4.58
	09:40	130	55	2.42	4.61
	09:40	140	50	2.1	3.80
	09:52	150	47	2.25	4.16
	09:52	160	62	2.49	4.81
	09:52	170	22	1.31	2.36
	10:06	180	33	1.45	2.56
	10:06	190	30	2.33	4.36
	10:06	200	10	1.33	2.39
	10:18	210	17	1.2	2.21
	10:18	220	13	2.13	3.87
	10:18	230	0	0	1.07
2-B (100 m)	10:32	230	13	1.25	2.27
	10:32	220	18	2.36	4.44
	10:32	210	15	1.56	2.74
	10:43	200	38	1.57	2.76
	10:43	190	32	1.79	3.15
	10:43	180	20	1.5	2.64
	10:56	170	33	2	3.58
	10:56	160	15	2.89	6.12
	10:56	150	17	1.7	2.98
	11:08	140	2	1	1.95
	11:08	130	3	1	1.95
	11:08	120	0	1.33	2.39
2-E (20 m)	13:18	0	0	0	1.07
	13:18	10	0	0	1.07
	13:18	20	3	2.5	4.84
2-C (50 m)	12:12	0	57	1.79	3.15
	12:12	10	40	2.46	4.72
	12:12	20	50	1.87	3.31
	12:24	30	48	2.07	3.73

Transect (distance)	Time (GMT)	X-wind distance (m)	Frequency (% of time)	Mean Intensity	Average Conc. (OUe/m³)
	12:24	40	35	2.33	4.36
	12:24	50	20	1.75	3.07
2-D (100 m)	12:39	70	8	1.6	2.81
	12:39	60	5	2	3.58
	12:39	50	3	1.5	2.64
	12:51	40	10	1.17	2.17
	12:51	30	7	1.25	2.27
	12:51	20	0	0	1.07
	13:04	10	7	1	1.95
	13:04	0	7	1	1.95
	13:04	-10	0	0	1.07

3.3.2. Ammonia

Ambient ammonia concentrations were measured at both farms using ALPHA samplers (deployed in triplicate). In addition, a DELTA denuder and a continuous AiRRmonia sampler were deployed at Whitelees farm (see Figure 3).

Measurements collected using ALPHA samplers are detailed in Table 18 and Table 19 for Whitelees and Glendevon farms respectively. An intercomparison of the ALPHA, DELTA and AiRRmonia samplers is shown in Table 20, illustrating that (discounting periods of instrument outage) the agreement between all three methods was very good. In addition, coefficients of variation for the triplicate ALPHA samplers (data not presented) were typically less than 5% illustrating that this method has suitable precision to provide robust data for model validation.

Polar plots were produced using the OpenAir package (Carslaw, 2012; Carslaw and Ropkins, 2012) from the AiRRmonia data for each of the 4 time periods that Alpha samplers were exposed over. These are shown in Figure 22 and illustrate the strong NH_3 signal from Whitelees farm, with little evidence of interference from other farm buildings or from the local grazing livestock. It is interesting to note that once emptied of livestock (Run 4 of Figure 22) the farm buildings no longer present a source of ammonia.

Table 18: ALPHA sampler NH_3 measurements at Whitelees Farm.

Site	OS X (m)	OS Y (m)	Dist. (m)	Concentration (µg m^{-3})			
				Run 1	Run 2	Run 3	Run 4
White1	291345	646530	114	66.5	44.9	57.0	4.1
White2	291468	646458	150	50.2	31.1	26.1	1.2
White3	291521	646628	289	13.2	9.1	9.6	0.8
White4	291629	646994	652	3.9	2.9	4.2	0.8
White5	291405	646303	141	13.0	16.3	16.0	0.6
White6	291294	646177	243	4.0	4.8	5.6	0.4
White7	291032	646427	291	3.4	8.9	3.3	0.7
White8	291205	646812	411	11.4	6.8	5.5	1.4
White9	291446	646829	429	6.7	5.4	6.2	1.2

Table 19: ALPHA sampler NH_3 measurements at Glendevon Farm.

Site	OS X (m)	OS Y (m)	Dist. (m)	Concentration (µg m^{-3})			
				Run 1	Run 2	Run 3	Run 4
Glen 1	307287	685511	75	101.7	69.7	44.9	60.3
Glen 2	307347	685564	151	33.9	22.3	15.3	21.8
Glen 3	307431	685621	249	18.0	13.7	10.5	11.9
Glen 4	307491	685660	319	12.2	10.3	8.6	7.7
Glen 5	307495	685525	251	34.8	44.8	30.6	22.6
Glen 6	307365	685423	108	221.9	247.7	125.0	87.6
Glen 7	307079	685365	195	13.9	13.8	39.9	41.9
Glen 8	306934	685549	342	4.4	7.6	6.4	3.7
Glen 9	307223	685727	288	3.8	21.5	1.7	2.1

Table 20: Intercomparison of ammonia samplers at Whitelees Farm.

Start (GMT)	End (GMT)	DELTA (µg m^{-3})	ALPHA (µg m^{-3})	AiRRmonia (µg m^{-3})
29/08/2013 11:59	17/09/2013 10:40	39.7	44.4	81.7[£]
17/09/2013 10:42	02/10/2013 11:00	51.7	51.2	56.5
02/10/2013 11:00	14/10/2013 12:04	101[*]	61.6	56.7
21/10/2013 13:31	04/11/2013 11:02	3.94	4.2	2.3[$]

*Notes: *: DELTA sampler pump failures occurred for approximately 50% of the time; £: 12% data capture, $: 78% data capture.*

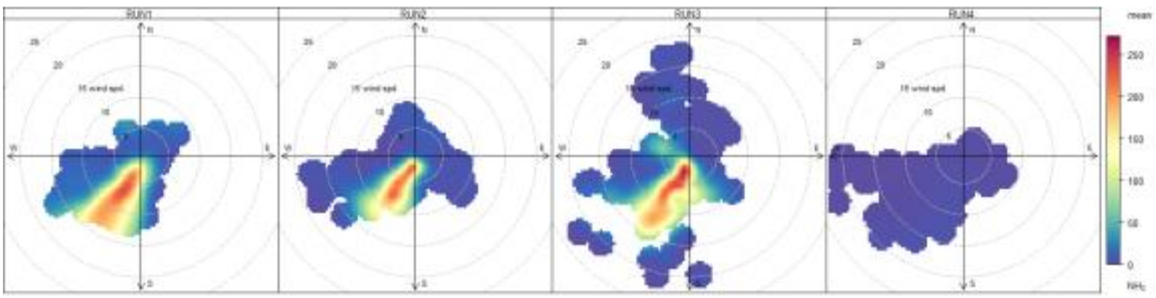


Figure 22: Polar Plots of ammonia concentration by wind direction and wind speed for the 4 sample runs at Whitelees Farm produced using the OpenAir package.

3.3.3. PM_{10}

PM_{10} concentrations were recorded at Whitelees farm (site "White1") using an OSIRIS monitor between the 6th of August and the 4th of November 2013 at a time resolution of 15 minutes. The 15-minute data were integrated to a resolution of 1 hour and 24 hours for use in the validation exercise. Data capture during the first 8 days of the deployment was poor due to power outages although there were no further issues following this initial period. As a comparison with the AiRRmonia data shown in Figure 22, PM_{10} data are shown in Figure 23 for the 4 ALPHA sampler runs at Whitelees farm. The results illustrate the PM_{10} concentrations do not show the same strong signal from the farm buildings found for the ammonia data, and clearly some other significant sources are present. In addition, it is clear that Run 4 of Figure 23 demonstrates a signal from the location of the farm (south-west) when the buildings are empty and ventilation systems switched off. This suggests that re-suspended dust may be a significant factor in ambient PM_{10} exposure around poultry buildings.

An intercomparison was conducted between the OSIRIS and the DUSTTRAK (used for measuring the concentration of PM_{10} in the building vents). The results of this intercomparison are shown in Table 21 and illustrate that a relatively poor comparison was found on the 19th of September and a good comparison was achieved on the 26th of September. It is likely that the reason for the poor performance on the 19th was due to interference from water droplets as the DUSTTRAK did not have a heated air inlet. Such interference would not have affected the source term measurements made using the DUSTTRACK within the building ducts.

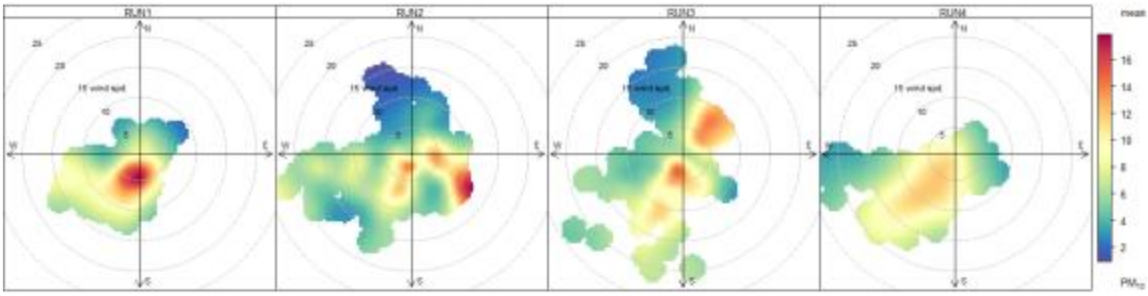


Figure 23: Polar Plots of PM_{10} concentration by wind direction and wind speed for the 4 sample runs at Whitelees Farm produced using the OpenAir package.

Table 21: Intercomparison of OSIRIS and DUSTTRAK samplers at Whitelees Farm.

Start (GMT)	End (GMT)	OSIRIS ($\mu g\ m^{-3}$)	DUSTTRAK ($\mu g\ m^{-3}$)	Weather
19/09/2013 12:30	19/09/2013 12:45	6.0	10.9	Drizzle
19/09/2013 12:45	19/09/2013 13:00	2.5	9.2	Drizzle
26/09/2013 12:00	26/09/2013 12:15	6.7	7.1	Dry
26/09/2013 12:15	26/09/2013 12:30	8.1	9.1	Dry

4. Validation modelling results

The monitoring data described in the previous section was used to validate the SCAIL-Agriculture Tool applying the techniques as detailed in the main report.

4.1. Model setups

4.1.1. SCAIL

The SCAIL Agriculture tool was configured for each of the farm sites by selecting the Installation location as the centre-point of the farm building complex. The buildings on each farm were configured using the parameters shown in Table 22 and locating each building using the “Verify Location” button on the SCAIL-Agriculture interface. The livestock type for both farms was set to “Layers” with further details of “ventilated deep pit”. As “side of building” was selected for the fan location no further details on the ventilation system were required.

Table 22: Parameters used to configure each source in SCAIL-Agriculture for Whitelees and Glendevon farms.

Site	N. sources	Building Height	Fan Location	Livestock number	Housing floor area
Whitelees	8	4 m	Side of building	4500	539 m^2
Glendevon	5	4 m	Side of building	8954	1436 m^2 (except B1 = 1851 m^2)

4.1.2. AERMOD

AERMOD was configured similarly to SCAIL although with accurate information on the location and orientation of each building as well as individual locations for the ventilation fans. The same emission parameters were used in AERMOD as were applied in SCAIL and the buildings configured in AERMOD were also set to a height of 4 m.

4.2. Comparison of emissions data

Table 23 presents the comparison of emission data between SCAIL Agriculture and the field measurements. Emission rates of PM_{10} and odour that calculated by SCAIL-Agriculture were higher than those that were measured, though the calculated ammonia emission rate was lower than was measured.

It is useful to compare the ventilation rates of the buildings with typical values from the literature (detailed in Table 2-D of the SCAIL Agriculture Final report from *Seedorf et al., 1998).* The measured ventilation rates from Whitelees farm were 53 m^3/s and these compare with a literature value of 42 m^3/s whilst for Glendevon Farm the measured ventilation rate of 116 m^3/s compares with a literature value of 63 m^3/s. For Glendevon Farm the building ventilation was set to continuous operation during the period of the measurements to provide consistency in the results and therefore it is possible that the ventilation rate applied in the emissions calculations may be an overestimate of typical values. Nevertheless, the reasonable agreement between the ventilation rate estimates and literature values adds a level of confidence that the measured data are realistic.

Table 23: Comparison of measured emission rates with the predictions of SCAIL-Agriculture.

Site	Whitelees			Glendevon		
	PM_{10} (Kg)	Odour (KOu)	Ammonia (Kg)	PM_{10} (Kg)	Odour (KOu)	Ammonia (Kg)
SCAIL-Agriculture	7.20E+02	1.59E+09	7.20E+03	8.95E+02	1.98E+09	8.95E+03
Measured	2.65E+02	4.56E+08	3.05E+04	7.07E+02	7.93E+08	4.03E+04
measured: SCAIL	0.37	0.29	4.24	0.79	0.40	4.50

4.3. Comparison of ammonia data

SCAIL agriculture was run for the following scenarios for comparison with the measured long-term Alpha sampler data:

- *Default (Edinburgh) meteorological data (Realistic Mode)*
    - *SCAIL-Agriculture calculated emissions (Scenario ER1)*
    - *Measured emission data (Scenario ER2)*
- *Default (Edinburgh) meteorological data (Conservative Mode)*
    - *SCAIL-Agriculture calculated emissions (Scenario EC1)*
- *On site meteorological data (Realistic mode)*
    - *SCAIL-Agriculture calculated emissions (OR1)*
    - *Measured emission data (OR2)*

In addition the results were compared with an AERMOD simulation using Edinburgh meteorological data and the calculated emissions data (Scenario AER1).

It should be noted that the average measured data for Whitelees farm only included Runs 1 – 3 as the farm was empty for Run 4 and therefore a comparison with SCAIL-Agriculture would not be helpful.

The results of the comparison are shown in Table 24 and Figure 24. Key points from this comparison are as follows

- *A very good agreement was found between SCAIL-Agriculture (ER1) and AERMOD (AER1) for both sites.*
- *The use of the Edinburgh meteorological data (ER1, ER2) resulted in higher predictions than the on-site data (OR1, OR2) for both sites. The use of Edinburgh meteorological data with measured emissions (ER2) resulted in concentrations that were significantly higher than the measured data at both sites.*
- *For Whitelees Farm, the use of onsite meteorological data and the default SCAIL emissions (OR1) provided concentrations that were significantly lower than the measured data.*
- *A good agreement was found between the OR2 scenarios and measured data for Whitelees farm, although for Glendevon farm this scenario over-predicted concentrations. This may be due to the aforementioned overestimation of building ventilation rates.*
- *Overall the default SCAIL-Agriculture configuration (ER1) provided the best agreement with the measured data meeting all the Chang and Hanna (2004) model acceptability criteria. This seems to be due to the cancelling effect of the higher concentrations predicted by the use of the Edinburgh meteorological data and the lower estimation of emissions for this scenario. A scatter plot showing the comparison between the ER1 data and SCAIL Agriculture is shown in* Figure 25*.*

Table 24: Comparison of measured ammonia concentrations with the predictions of SCAIL-Agriculture and AERMOD.

Site	Distance (m)	Ammonia concentration (µg m-3)						
		Measured	ER1	EC1	ER2	OR1	OR2	AER1
White1	114	55.2	35.8	48.7	144.9	15.9	60.5	32.5
White2	150	37.2	30.8	33.9	123.8	9.7	34.4	26.9
White3	289	10.7	19.2	16.5	74.8	5.6	16.9	17.1
White4	652	3.5	8.0	7.5	27.2	2.9	5.7	7.8
White5	141	15.0	12.8	36.7	47.6	4.2	11.3	11.2
White6	243	4.7	8.6	19.9	29.9	4.3	11.4	7.7
White7	291	5.8	9.7	16.4	34.4	5.1	15.0	8.6
White8	411	8.3	6.2	11.7	19.4	2.9	5.4	5.5
White9	429	6.0	9.9	11.3	35.1	3.8	9.2	8.9
Glen1	75	72.4	88.1	121.4	390.3	50.8	222.7	57.7
Glen2	151	24.3	34.9	37.6	151.2	18.7	78.2	32.7
Glen3	249	13.9	23.0	21.4	97.4	11.6	46.2	21.9
Glen4	319	9.9	18.1	16.2	75.7	9.1	35.1	17.4
Glen5	251	34.1	21.1	21.2	88.8	16.1	66.4	21.6
Glen6	108	180.1	62.8	56.0	276.6	80.5	356.1	54.3
Glen7	195	25.1	13.7	28.1	55.5	11.5	45.6	14.0
Glen8	342	5.5	8.3	15.0	31.5	22.0	92.8	8.1
Glen9	288	8.7	9.7	18.2	37.6	8.6	32.8	9.6
Summary Statistics (shaded values illustrate meeting the Chang and Hanna, 2004 criteria)								
FB			0.16	-0.05	-1.10	0.54	-0.80	0.34
MG			0.89	0.66	0.23	1.58	0.48	0.98
NMSE			1.32	1.37	3.61	1.77	2.16	1.80
VG			1.31	1.68	11.00	1.82	2.92	1.31
FAC2			0.89	0.56	0.06	0.56	0.50	0.83

A further comparison was made between the continuous ammonia data recorded with the AiRRmonia and SCAIL-Agriculture. In order to remove some of the inherent variability associated with the prediction of short-term air concentrations the measured and modelled data were analysed to provide daily-averaged values. Overall 50 days of data were available for this comparison. SCAIL-Agriculture was run using the measured emission data from the site and the on-site meteorological data (scenario OR2). A scatterplot of this comparison is shown in Figure 26 and the summary statistics are shown in Table 25. These results show that SCAIL-Agriculture met all five of the performance criteria from Chang and Hanna (2004).

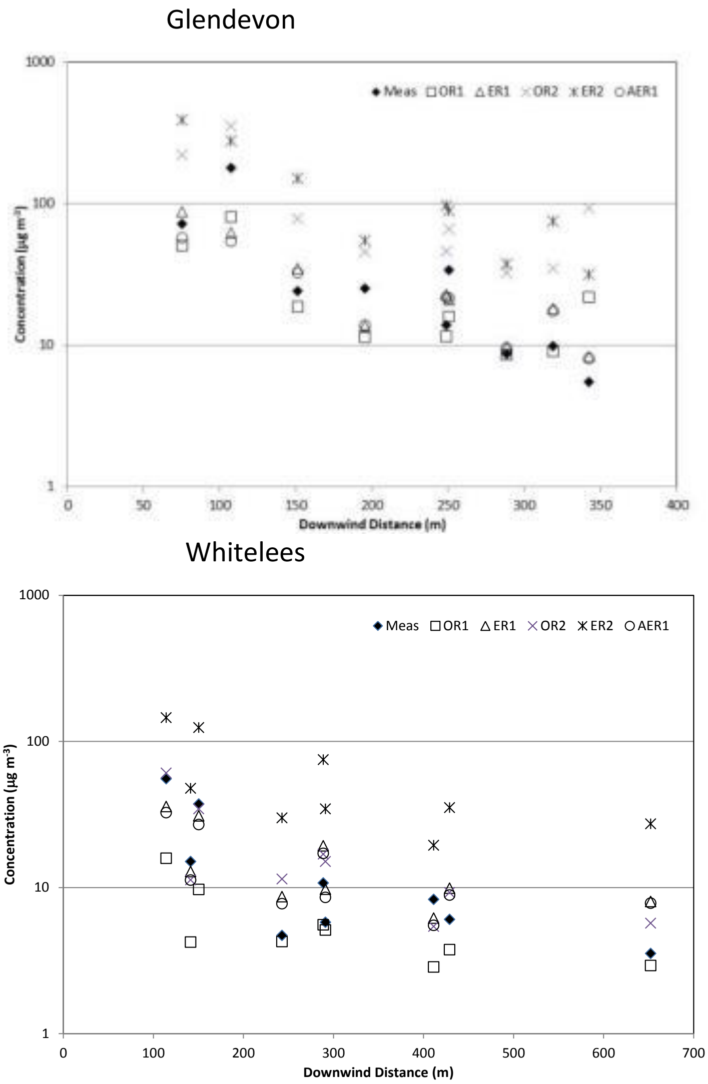


Figure 24: Plots of ammonia concentration vs. downwind distance for Glendevon and Whitelees farms.

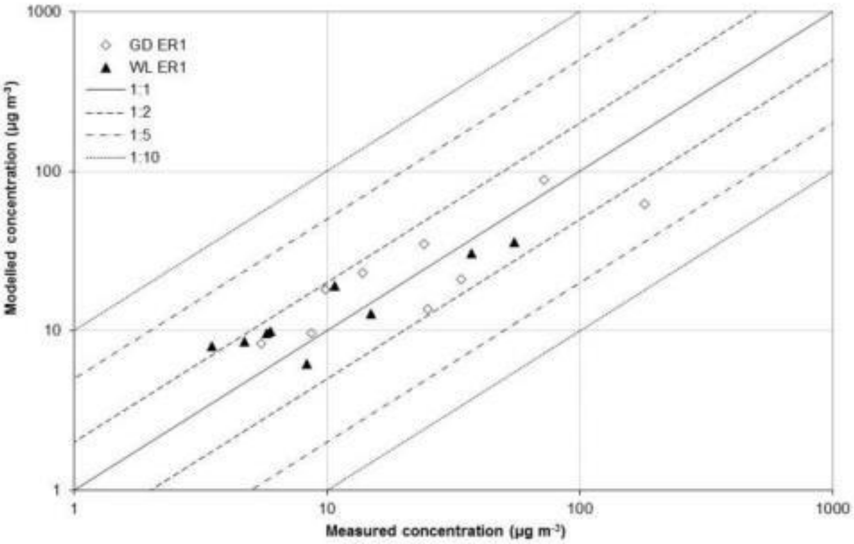


Figure 25: Scatter plot of measured and modelled ammonia concentrations for the default configuration of SCAIL-Agriculture for Glendevon and Whitelees farms.

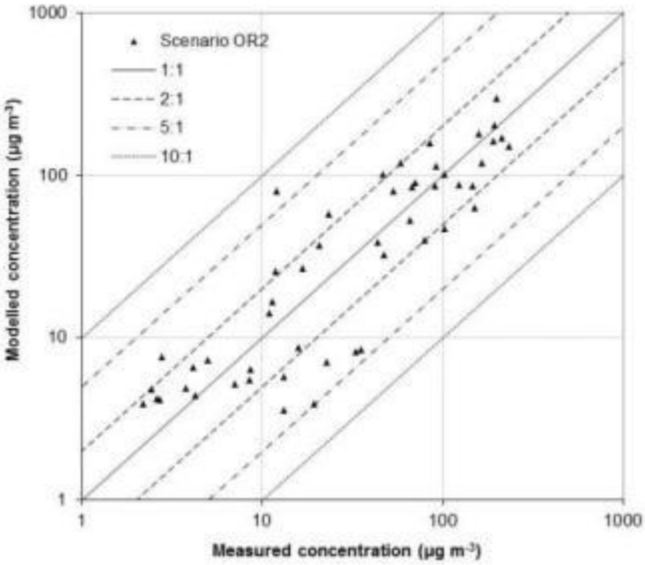


Figure 26: Summary of the performance indicator values for the different model runs and source parameterisations for the Whitelees 24 hour ammonia concentration dataset. Shaded cells represent values that meet the acceptability criteria.

Table 25: Summary of the performance indicator values for the different model runs and source parameterisations for the Whitelees 24 hour ammonia concentration dataset. Shaded cells represent values that meet the acceptability criteria.

Run / Parameterisation No.	FB	MG	NMSE	VG	FAC2
OR2 (SCAIL-Agriculture on-site meteorological data and measured emissions)	0.013	1.019	0.330	1.622	72%

4.4. Comparison of PM_{10} data

As noted in the previous section, the PM_{10} data measured at Whitelees farm did not clearly identify the farm buildings as the dominant emission source. The data in fact illustrates that other sources dominate the PM_{10} concentration field and also provides evidence that resuspension of surface dusts also may be significant. Re-suspension emissions are not included in SCAIL-Agriculture.

In order to account for some of the background issues the measured PM_{10} data were filtered as follows:

- When wind directions are > 245 degrees and less than 155 degrees then the recorded concentrations are assumed to be unrelated to the farm and therefore "background values".
- Background values for concentrations recorded when wind directions are between 155 degrees and 245 degrees are taken from the last recorded concentration outside of this wind sector.

Figure 27 shows a PolarPlot of PM_{10} concentration vs wind speed and direction for the entire monitoring period. It illustrates the multitude of potential sources of PM_{10} in the environs of Whitelees farm and the position of the 90-degree wind sector referred to above for filtering the PM_{10} data.

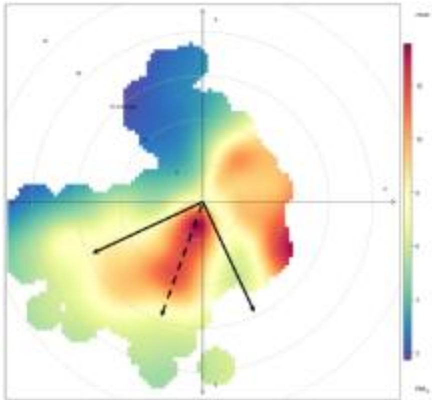


Figure 27: PolarPlot of PM_{10} concentrations Vs wind speed and direction for Whitelees farms. A 90-degree wind sector is shown for use in filtering the background PM10 data.

A statistical summary of these data is shown in Table 26. These data illustrate that the default SCAIL-Agriculture configuration (Scenario OR1) met 3 of the 5 model acceptability criteria of Chang and Hanna (2004). A significantly poorer performance was obtained when the measured emission data were used (Scenario OR2) and in this case none of the acceptability criteria were met. As a note of caution however it is possible that re-suspension of dust may also have contributed to the measured dataset.

Table 26: Summary of the performance indicator values for the different model runs and source parameterisations for the Whitelees 24 hour PM_{10} concentration dataset. Shaded cells represent values that meet the acceptability criteria.

Run / Parameterisation No.	FB	MG	NMSE	VG	FAC2
OR1 **(SCAIL-Agriculture on-site meteorological data and default emissions)**	0.201	1.087	1.154	5.372	0.319
OR2 **(SCAIL-Agriculture on-site meteorological data and measured emissions)**	1.072	2.938	4.837	17.047	0.277

Scatterplots showing the comparison between SCAIL-Agriculture and the monitored PM_{10} data are shown in Figure 28 for Scenarios OR1 and OR2.

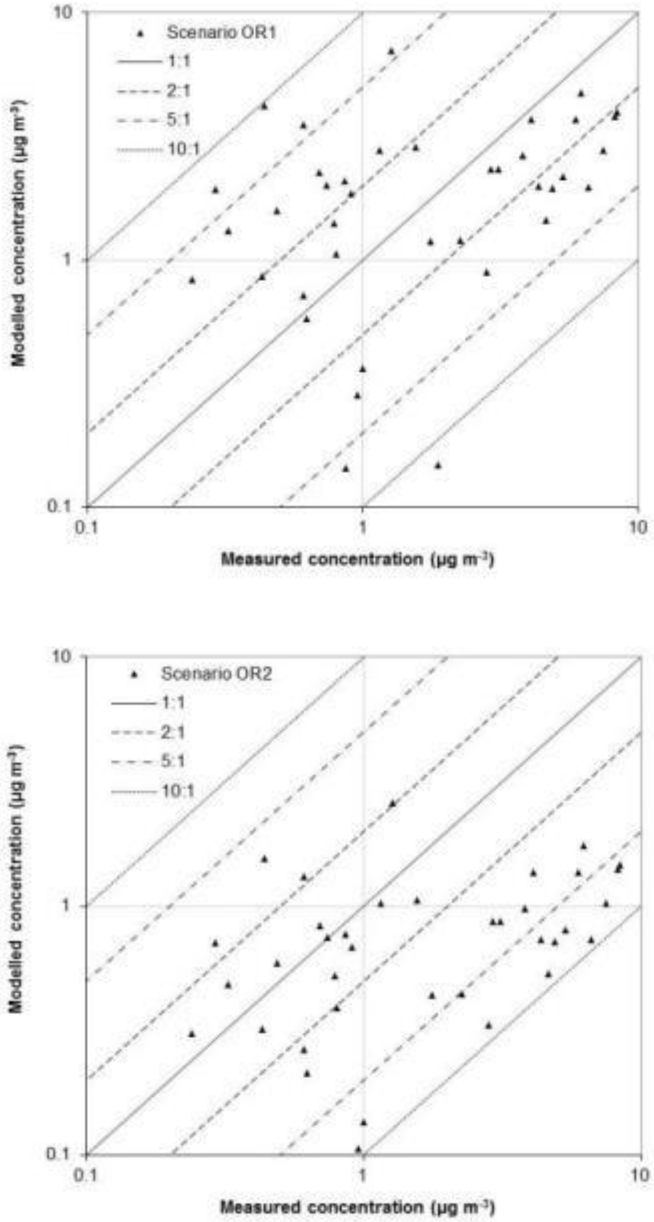


Figure 28: Scatter plot of measured and modelled daily averaged PM_{10} concentrations for the OR1 and OR2 configuration of SCAIL-Agriculture for Whitelees farm.

4.5. Comparison of Odour data

The meteorological data recorded during the field odour sampling is shown in Table 27 and Table 28 for Glendevon and Whitelees farms respectively. Odour concentrations were modelled using SCAIL-Agriculture applying the on-site meteorological data and calculated emissions (OR1) and measured emissions (OR2) scenarios. Scatterplots of the point-by-point comparison of measured and modelled odour concentrations for these scenarios are shown in Figure 29 and Figure 30 for Glendevon and Whitelees Farms respectively. These results show a considerable degree of scatter, which is to be expected for a point-to-point comparison of short term concentrations. The modelled estimates of odour concentrations are also clearly improved through the use of the measured emission data. A statistical comparison of the measured and modelled odour dataset is shown in Table 29 illustrating the improved statistics obtained by the use of the measured odour emission data. The Chang and Hanna (2004) model acceptability criteria were only met for determination of Geometric Mean Bias (MG) for the OR2 scenario.

Table 27: Meteorological data for the odour sampling at Glendevon Farm.

Date / Time GMT	Wind speed (m/s)	Wind Direction (degrees)	Relative humidity (%)	Temp. (^oC)	Rainfall (mm)	Solar Radiation (W m^{-2})	Cloud Cover (oktas)
18/09 12:00	7.1	284.2	71.0	12.8	0.0	465.4	5
18/09 13:00	8.1	285.0	69.4	13.1	0.3	504.8	3
18/09 14:00	10.3	290.5	63.3	13.3	0.0	472.4	0
18/09 15:00	9.4	290.6	63.4	13.5	0.0	387.2	0
18/09 16:00	10.9	294.3	63.6	13.1	0.0	226.3	5
25/09 13:00	3.3	102.0	100.0	11.8	0.0	89.1	8
25/09 14:00	3.2	95.2	100.0	11.7	0.0	51.4	8
25/09 15:00	2.8	94.9	100.0	11.8	0.0	60.5	8
25/09 16:00	3.2	98.6	98.2	12.3	0.0	85.0	8

Table 28: Meteorological data for the odour sampling at Whitelees Farm.

Date / Time GMT	Wind speed (m/s)	Wind Direction (degrees)	Relative humidity (%)	Temp. (^oC)	Rainfall (mm)	Solar Radiation (W m^{-2})	Cloud Cover (oktas)
19/09 10:00	2.6	117.6	92.5	7.7	0.0	96.3	8
19/09 11:00	2.6	93.2	93.4	8.2	0.0	93.2	8
19/09 12:00	4.3	212.4	92.8	10.1	0.2	132.4	8
19/09 13:00	9.6	248.5	90.9	11.2	0.2	136.8	8
26/09 09:00	2.6	88.3	84.2	9.0	0.0	265.4	5
26/09 10:00	3.0	105.3	77.7	10.5	0.0	404.6	3
26/09 11:00	3.4	117.2	68.9	11.9	0.0	445.3	4
26/09 12:00	1.8	124.7	68.4	11.9	0.0	448.7	4
26/09 13:00	1.1	110.9	66.5	12.2	0.0	250.1	7
26/09 14:00	1.1	199.0	65.1	12.9	0.0	174.9	7

Table 29: Summary of the performance indicator values for the different model runs and source parameterisations for the Odour concentration dataset. Shaded cells represent values that meet the acceptability criteria.

Run / Parameterisation No.	FB	MG	NMSE	VG	FAC2
Glendevon OR1	-1.429	0.431	16.231	438.542	0.256
Glendevon OR2	-0.824	1.077	5.337	217.156	0.233
Whitelees OR1	-1.418	0.214	12.168	241.575	0.233
Whitelees OR2	-0.521	0.738	1.868	24.595	0.289

It should be noted that the Chang and Hanna (2004) criteria were developed for the comparison of chemical species that can be precisely measured in the atmosphere and for arc-wise maximum concentrations determined over a long averaging period.

Figure 31 shows the direct comparison of measured and modelled odour concentrations at two transects. This figure illustrate that there is a reasonable agreement between measured and modelled odour concentrations although the measured dataset clearly demonstrates higher variability than the modelled dataset. This is expected and is due to the use of hourly-averaged meteorological data in the model and the inherent variability of atmospheric processes along with, of course, the variability associated with any quantitative measurement determined from the human nose.

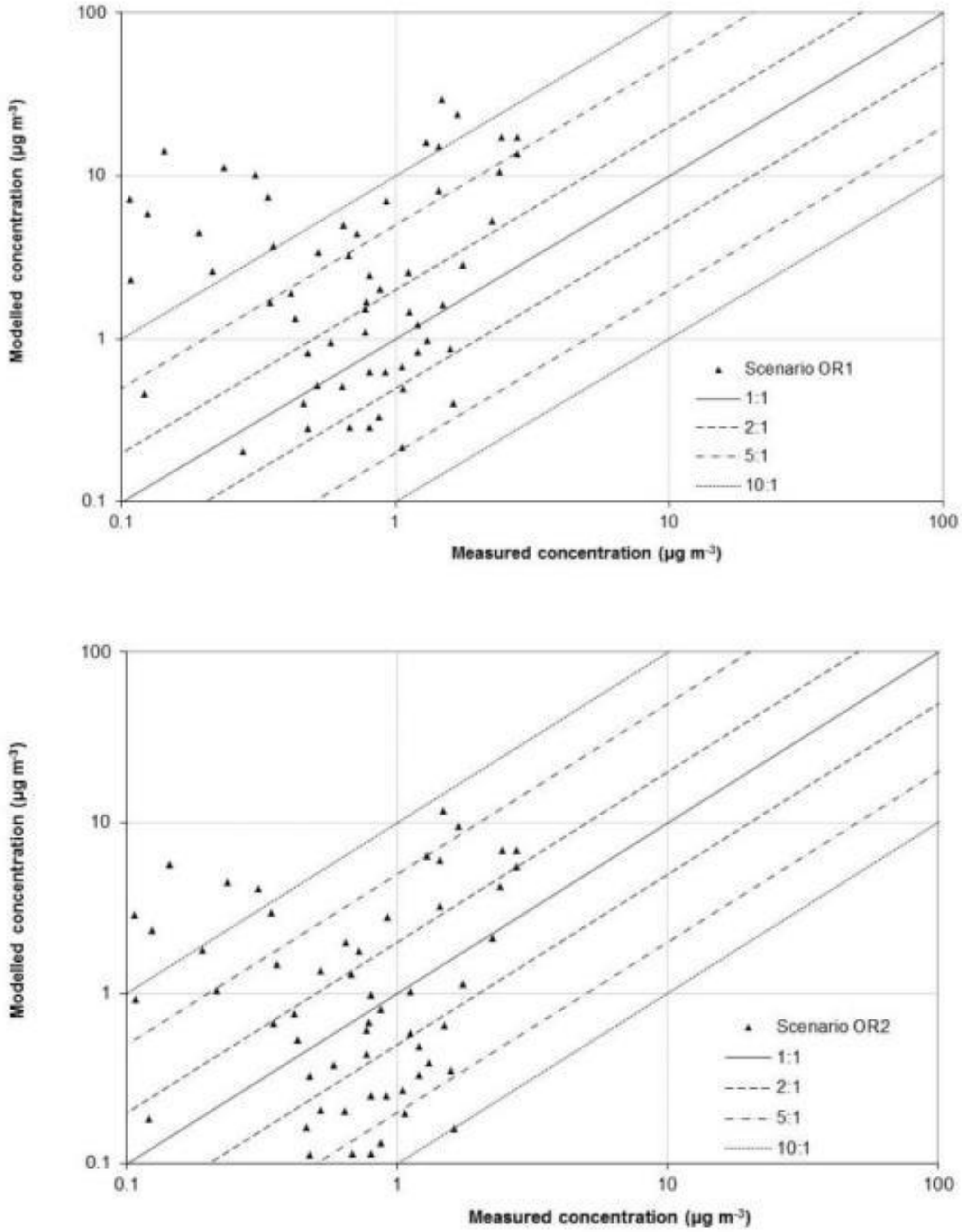
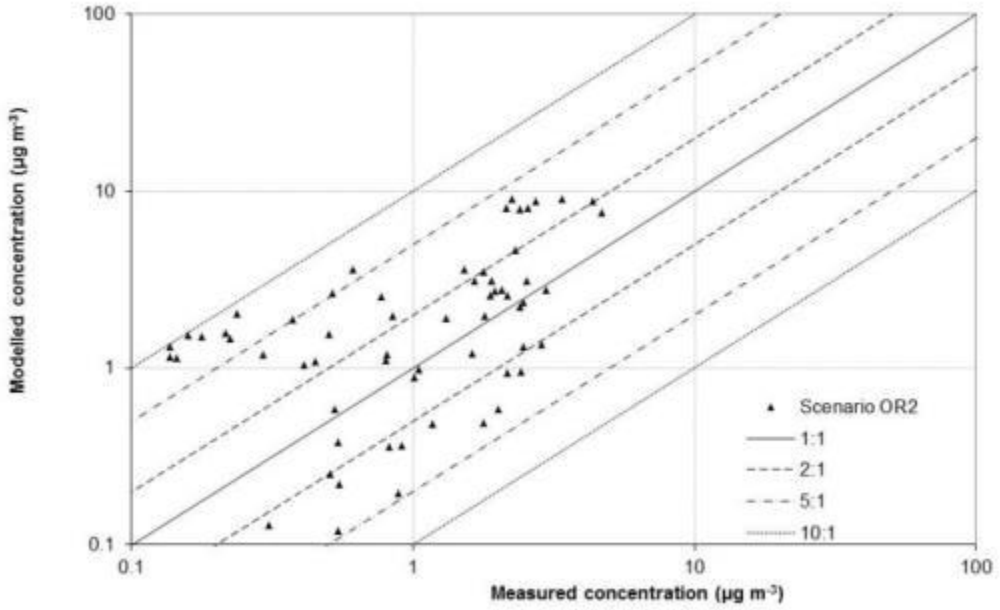


Figure 29: Scatterplots comparing measured and modelled odour concentrations at Glendevon farm for scenarios OR1 and OR2.



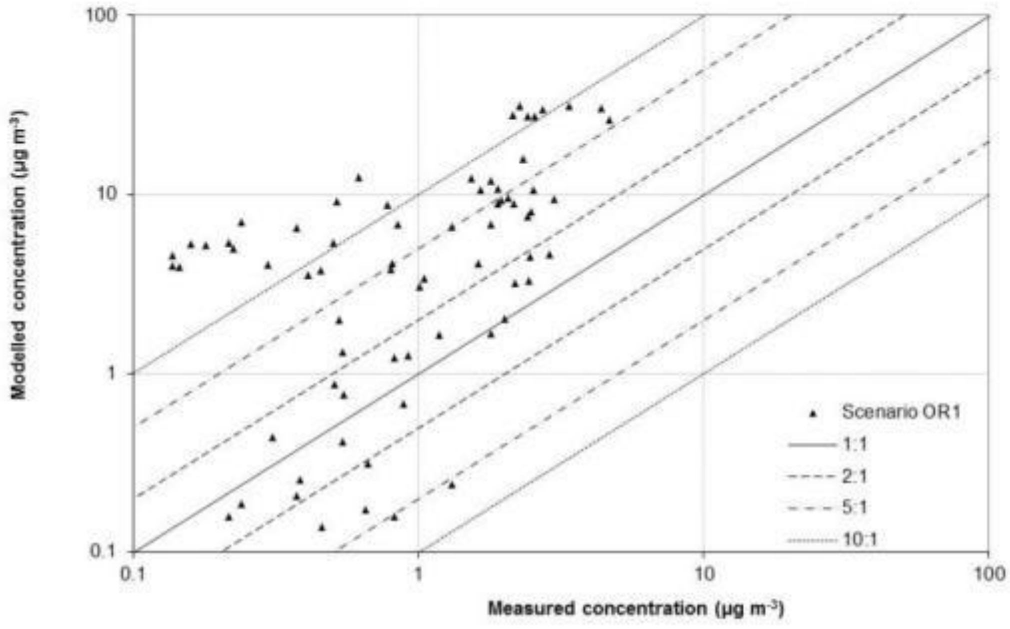


Figure 30: Scatterplots comparing measured and modelled odour concentrations at Whitelees farm for scenarios OR1 and OR2.

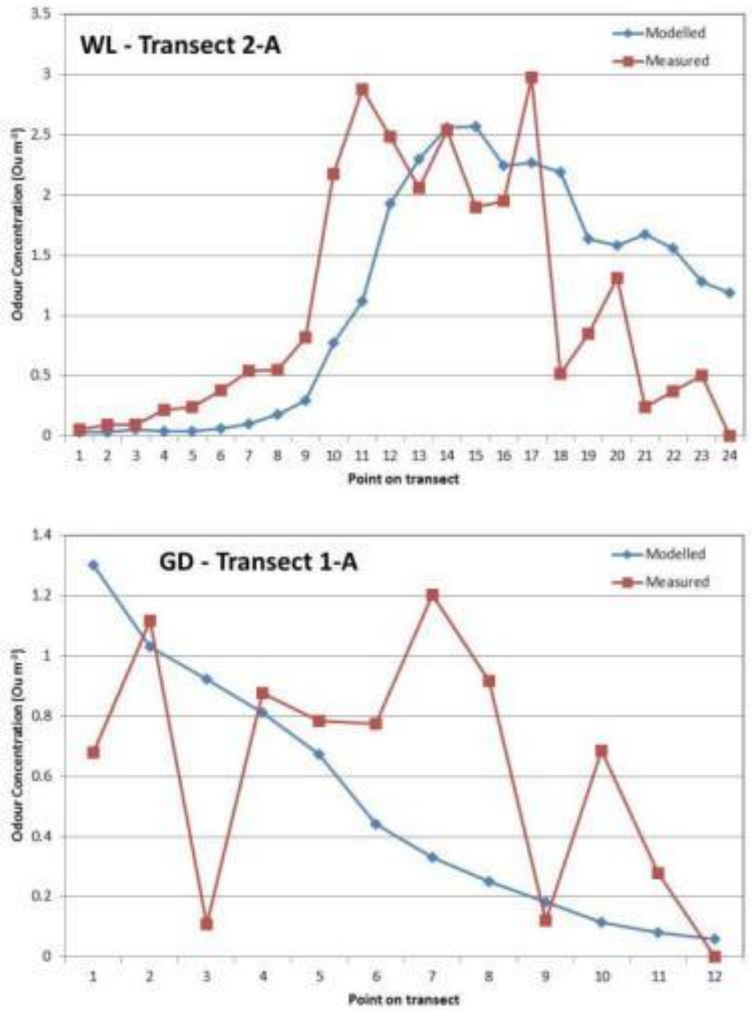


Figure 31: Comparison of measured and modelled odour concentrations at on transects at Glendevon farm (GD) and Whitelees Farm (WL) for scenario OR2.

5. Conclusions

A detailed set of model validation experiments were conducted at two farm sites in Central Scotland collecting odour, ammonia and airborne particulate data as well as recording on-site meteorological information. The following data were collected.

- *Continuous monitoring of meteorological data over a period of approximately three months at Whitelees and Glendevon Farms.*
- *Continuous monitoring of ammonia and airborne particulate concentrations was conducted over a period of approximately three months at Whitelees Farm.*
- *Monitoring of ammonia concentrations at nine locations around Whitelees and Glendevon Farms for a period of approximately three months using passive diffusion samplers (Alpha Samplers)*
- *Monitoring of ammonia, odour and PM_{10} emissions from the buildings at Whitelees and Glendevon Farms on two occasions.*
- *Monitoring ambient odour concentrations on transects at Whitelees and Glendevon Farms on two occasions.*

Measured emission data were relatively self-consistent between the two monitoring periods conducted at each farm. Measured emissions of ammonia were found to be higher than were predicted using the emission factors in SCAIL-Agriculture whilst measurements of PM_{10} emission and odour emission were lower than those predicted using the emission factors in SCAIL-Agriculture.

Measured ambient concentrations of ammonia recorded using ALPHA samplers were found to agree well with the default configuration of SCAIL-Agriculture, with the model meeting all the acceptability criteria of Chang and Hanna (2004). In addition, a good agreement was found between SCAIL-Agriculture and a detailed AERMOD model of atmospheric dispersion from both farms. Ambient ammonia concentrations recorded using the continuous AiRRmonia monitor were also found to agree well with SCAIL Agriculture when configured using on-site meteorological data and measured emission rates, again meeting all the acceptability criteria of Chang and Hanna (2004).

Measured PM_{10} concentrations showed a relatively weak signal from Whitelees Farm, illustrating that other PM_{10} sources (either local or distant) were significant contributors. A filtering process was used to attempt to correct the measured data to remove these “background” contributions and a comparison of daily-averaged concentrations was made with the predictions of the SCAIL model. This comparison illustrated that, when configured with the default emissions parameters, SCAIL-Agriculture met 3 of the 5 model acceptability criteria of Chang and Hanna (2004).

Odour concentrations measured on transects by field “sniffers” around both farms were compared with the model predictions. It should be noted that there is a high level of inherent uncertainty associated with the comparison of data determined with the human nose over a short time period and the predictions of a numerical model configured with hourly averaged meteorological data. However, it was clear that, whilst only one of the five acceptability criteria of Chang and Hanna (2004) were met, the model (when configured using measured emissions data) provided realistic estimates of the magnitude of ambient concentrations and also their spatial distribution.

In conclusion the SCAIL-Agriculture model was found to broadly meet recognised acceptability criteria for the prediction of ammonia, PM_{10} and odour concentration arising from farm buildings. There are however a number of areas where further research could clearly improve the assessment of agricultural sources. These are as follows:

- *Improvements to the emissions datasets used to derive emission factors that are included in the tool.*
- *Investigations as to the impact of local vs. regional meteorological data on the performance of assessment codes.*
- *Further research into PM_{10} levels around farm buildings and the impact of re-suspended dusts on local air concentrations.*

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