

A review of the limitations and uncertainties of modelling pollutant dispersion from non-point sources

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ABSTRACT

This study into the limitations and uncertainties of modelling pollutant dispersion from non-point sources begins with an extensive review of available literature relating to the dispersion modelling of agricultural and bioaerosol sources. One of the outcomes of the literature review is the compilation of a parameter space of source configurations that have previously been used in the modelling of these non-point source types. A detailed investigation into the way in which the ADMS and AERMOD dispersion models represent non-point sources is presented, including an inter-comparison of model behaviour for the range of model input parameters obtained from the literature. Datasets suitable for model evaluation studies were identified during the literature review and results from an ADMS and AERMOD model evaluation exercise is presented using measured data from three agricultural field campaigns and one bioaerosol study. Overall conclusions from the study and recommendations for further work are given.

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The views expressed in this report are those of the authors, and do not necessarily represent the views of ADMLC or of any of the organisations represented on it

EXECUTIVE SUMMARY

This study comprised three tasks: a literature review; a series of idealised scenario analyses that demonstrate model behaviour when modelling non-point sources; and a model evaluation exercise using data from four measurement campaigns. The modelling has been performed using the ADMS and AERMOD dispersion models. The main conclusions from each of these tasks are given in this summary. References to the main body of the report have been given where appropriate. The project findings in terms of overall conclusions and recommendations for further work are presented in Section 5.

Task 1: Literature review

A comprehensive literature review was undertaken for this project (Task 1), including consideration of: guidance documents relating to current practice; non-point source dispersion model evaluation studies; and documents detailing field campaigns. These documents were reviewed in order to collate a parameter space of commonly used values for describing agricultural and bioaerosol sources in dispersion models. These parameters were then used as input for the idealised modelling scenarios (Task 2). Further, the datasets described in the literature that had the potential for use as model evaluation case studies were highlighted. The owners of these datasets were then contacted and where possible datasets obtained; this proved to be a difficult and time-consuming task.

The Environment Agency documentation H1 Annex B (EAH1 B, 2011) and the AQMAU guidance document (EA AQMAU, 2010) on modelling ammonia from intensive farms are useful references when performing dispersion modelling from agricultural sources. The authors would generally agree with the recommended methodologies for representing the agricultural source types proposed in EA AQMAU (2010) but have one comment:

- Using a low-level line source to represent, for instance, gable-end fans may lead to very different results in ADMS and AERMOD (refer to Figures 9 and 10).

The SCAIL Agriculture update report (Hill *et al.*, 2014) includes a comprehensive review of datasets that are potentially useful for validating dispersion models. However, the authors of this study were unable to obtain access to the majority of these datasets. Of these, the Whitelees and Glendevon datasets appear to be most robust. The Whitelees dataset included near source (approximately 60 m distant) continuous monitoring that allowed detailed statistical analyses of model results using the range of non-point source types.

The Defra poultry dataset (Demmers *et al.*, 2009, 2010) was of considerable use to this project because measurements were taken at a number of distances downwind of the sources. This field campaign also included measurements from

a range of farm types. Similarly, the Defra bioaerosol study (Williams *et al.*, 2013) was of use because measurements were taken downwind of the source.

- The Sniffer Whitlees dataset (Hill *et al.*, 2014), Defra poultry dataset (Demmers *et al.*, 2009, 2010) and the Defra bioaerosol dataset (Williams *et al.*, 2013) were selected as the most robust datasets available for use in the case study model evaluation exercise undertaken (Task 3).

Douglas (2013) was of interest to the modelling of bioaerosols for this study, in particular the list of recommendations that relate to modelling bioaerosol emissions from open windrow composting facilities in the UK.

The limitations and uncertainties relating to dispersion modelling of non-point sources were discussed in relation to: meteorology, emission rates, source definition, observation uncertainty, general model performance and model limitations. Using a risk-assessment type approach, these aspects were given an 'overall uncertainty rating' by combining the relative uncertainty with the impact of a poor estimate. The following aspects have been classified as most uncertain (refer to Table 9):

- Emission rates of odour and bioaerosol from biowaste and composting processes;
- Observation uncertainty of odour and bioaerosol measurements from agriculture, biowaste and composting processes;

The literature review involved consideration of a wide range of dispersion models. Although ten models were initially highlighted as suitable for inclusion in the model sensitivity and evaluation exercises relating to the modelling of agricultural and bioaerosol sources, project limitations resulted in only ADMS and AERMOD being used in the modelling exercises as these are the most widely used models in the UK.

- Project constraints resulted in only ADMS and AERMOD being considered in the modelling exercises.

A detailed description and comparison of the ADMS and AERMOD model formulations with regard to modelling non-point sources has been presented. Conclusions from this comparison include:

- ADMS and AERMOD model three base source types with respect to modelling of non-point sources (refer to Tables 12 and 13), specifically: area, volume and jet sources. In ADMS, the jet source may be directed in any direction but the effect of buildings is not allowed for; in AERMOD the jet source is limited to a horizontal wind-aligned release but allowance for buildings can be made.
- Neither ADMS nor AERMOD allow for the presence of buildings when modelling line, area or volume sources.
- Volume sources are treated as passive in both ADMS and AERMOD.

- In ADMS buoyancy and initial momentum are taken into account for line and area sources. A 'lift-off' criterion is applied to ground level sources so that the initial buoyancy and momentum have no effect unless they are sufficient for the plume to leave the ground.
- AERMOD version 14134, which was used for this study, does not take into account buoyancy or initial momentum for line or area sources. AERMOD version 15181 (released towards the end of July 2015) includes an option for modelling buoyant line sources.

The literature review allowed a parameter space of inputs used for modelling agricultural and bioaerosol sources to be compiled.

- Tables 17 and 18 are a useful reference for those wishing to undertake dispersion modelling of these source types.

In addition, these tables define the parameter ranges for the idealised modelling (Task 2).

Task 2: Generic model behaviour

A modelling exercise has been performed with two main aims. The first is to compare predicted downwind concentrations for different source types and input parameters. The second aim is to demonstrate the similarities and differences between the two most widely used local dispersion models in the UK (ADMS and AERMOD) when agricultural and bioaerosol sources are modelled using non-point sources. The sources modelled have parameters that are representative of intensively farmed animals and composting windrows. Two sets of idealised modelling scenarios have been run: single meteorological conditions (Section 3.2) and annual runs (Section 3.3).

The single meteorological condition cases demonstrate in detail how predicted model concentrations vary with meteorological conditions, source dimensions and efflux parameters. Conclusions from these runs include:

- The **near-source** concentrations (within ~ 100 m from the sources) are very sensitive to the source configuration in terms of source: definition (line, area, volume), height, buoyancy and initial momentum.
- Using the non-point source configurations defined in Tables 23 and 24, without consideration of buoyancy or initial momentum, the **near-source** concentrations decrease in magnitude in the following order: line, area and volume sources. Jet source concentrations are similar in magnitude to those predicted when volume sources are used.
- Using identical meteorological conditions and source definitions as input to ADMS and AERMOD, predicted modelled concentrations are in most cases qualitatively similar, but sometimes differ in magnitude by a factor of two with AERMOD tending to give higher concentrations.

Relevant to these comparisons, included in the corrections in the AERMOD 15181 release, it states that previous versions of AERMOD may produce 'anomalous results for winds blowing nearly perpendicular to AREA/LINE sources in some cases'.

The annual scenarios include analyses of arc-average and arc-maximum concentrations. These cases demonstrate how, for typical real-world conditions, the source configuration impacts on overall predicted model concentrations. These annual calculations are of particular interest because period average (annual or seasonal) and high percentile concentrations are required for environmental impact assessments close to, for example, Sites of Special Scientific Interest (SSSIs). Conclusions from these runs include:

- At **>100 m** downstream the agricultural source configuration annual average concentrations (Figure 9):
 - are similar when comparing ADMS volume sources and non-buoyant low (ground level) and high (greater than 2 m) level line and area sources with initial momentum;
 - are similar when comparing AERMOD volume sources and high level line and area sources, but low-level line and area sources predict much higher values;
 - may be considerably lower when the release is buoyant and/or has initial momentum (ADMS does not model plume rise for volume sources; AERMOD version 14134 does not allow for plume rise for line, area or volume sources);
 - are lower when jet sources are modelled (note that the 'jet' source concentrations should not be compared directly between ADMS and AERMOD as the source definitions are not identical); and
 - are similar between ADMS and AERMOD for volume sources and high-level line and area sources.
- At **>100 m** downstream the bioaerosol source configuration annual average concentrations (Figure 10):
 - are similar when comparing ADMS volume sources and non-buoyant low level area sources with initial momentum, but the high-level area source predicts much lower values;
 - decrease in magnitude in the following order, when comparing AERMOD source configurations: area (low), volume and area (high);

* From the AERMOD 15181 release document 'Model Change Bulletin (MCB) 11 - AERMOD version 15181 changes by change type.'

- are orders of magnitude lower when the release is considered buoyant with initial momentum (ADMS does not model plume rise for volume sources; AERMOD version 14134 does not allow for plume rise for area or volume source), although this large reduction in concentration is directly related to the use of the Douglas (2013) exit velocity value of 2.95 m/s, which the authors consider too large; and
- are similar between ADMS and AERMOD for volume sources and high-level area sources.

The **overall conclusions** from these observations are:

- ADMS and AERMOD give similar predictions of annual average concentrations at >100 m downwind of the source when using volume and non-buoyant high level line and area sources.
- Modelling buoyancy and/or initial plume momentum significantly impacts on predicted modelled concentrations; currently this applies to ADMS line and area sources; the new version of AERMOD (15181) also allows for plume rise with line sources.
- The Douglas (2013) suggested value of 2.95 m/s for the exit velocity from windrows leads to very low concentrations beyond 100 m downwind of the source.

Task 3: Model evaluation

Four model evaluation studies have been undertaken during this project. The modelling has involved using a variety of appropriate non-point sources, and in some cases point sources, to represent the sources; the model evaluation studies were set up in ADMS and AERMOD in a consistent way. Specifically:

- Using the Whitelees dataset, continuously monitored concentrations of ammonia recorded approximately 60 m from four poultry sheds were modelled. Further, two sets of monthly concentrations from eight additional ammonia samplers were modelled, as was a series of odour measurements taken on a single day. The Whitelees study is considered to be the most robust agricultural dataset and therefore the conclusions drawn using this dataset are also the most robust.
- Using the Defra poultry dataset, PM₁₀ concentrations measured at varying distances downwind of the source (up to 400 m) were modelled at two farms. The modelling was performed separately for 'light' and 'dark' periods, which correspond to the animal activity rather than daylight conditions. Additional analyses relating to this dataset would be possible if information relating to the time of the measurements was made available.
- Using the Defra bioaerosol dataset, total bacteria concentrations measured at varying distances downwind of the source (up to 800 m)

were modelled at one site. The modelling was performed separately for six days, which were at various times of the year. For this dataset, the uncertainties in emissions lead to normalisation of the modelled concentrations to allow analyses of concentration decay only; the impact of buoyancy, initial momentum and deposition have been investigated.

There are many different real-world configurations for the farming of pig and poultry, both intensive and free range. Similarly, there are many composting sources from which bioaerosols and other pollutants are released. This study has only been able to consider model evaluation at a subset of these source types, specifically:

- Poultry sheds ventilated using upward pointing cowl fans;
- Tunnel ventilation poultry sheds, with and without emissions abatement technology (baffle); and
- A small composting site where only one source activity occurred at any one time.

The emissions for the poultry studies were estimated using concentration and ventilation measurements from the fan exits. Such calculations are likely to lead to more accurate emissions than those estimated from poultry numbers, but there is still significant uncertainty. For example, fan operation differs from shed to shed, and diurnally – clearly is it not feasible to model the emissions from each fan on each shed separately, even if the data were available. Therefore, the emissions used in the calculations are subject to uncertainty. Despite this, the following conclusions can be drawn:

- For Whitelees, the continuous monitoring measurements are a robust dataset that can be analysed statistically because of the large number of data points. The long-term ammonia and the odour modelling results support and add to the conclusions drawn. The main conclusion from this study is that it is important to model buoyancy and the initial momentum of the release if exit temperatures and velocities are significant. The upward pointing cowls on the Whitelees sheds are essentially jets, so it is unsurprising that the best model results are for this source type for ADMS (refer to Table 31). For AERMOD, a jet source can only be applied if the release is horizontal and wind aligned, so the best results are using a point source with a building (refer to Table 32). For the non-point source types where plume rise is neglected (volume sources in both ADMS and AERMOD, line and area sources in AERMOD version 14134), the models tend to over predict the observed concentrations.
- For the Defra poultry dataset Farm F, for some of the periods, the modelled concentrations represent the observations reasonably well. Buoyancy and initial release momentum influences the predicted modelled concentrations, and when this is not taken into account (volume sources in both ADMS and AERMOD, line and area sources in AERMOD version 14134), concentrations are over predicted. The non-point

sources appear to give a more reliable prediction of the decay than the 'with building' point source configuration (refer to Figure 32).

- The conclusions for Defra poultry dataset Farm G support those from Farm F. Specifically, for some of the periods, the modelled concentrations represent the observations reasonably well, but when buoyancy is not allowed for, concentrations have a tendency to be over predicted (note that the initial release momentum for this study is relatively unimportant due to the presence of a baffle at the fan exit).

Bioaerosol emissions are highly uncertain in addition to being related to the activity taking place at a site (for example, shredding, turning and screening at composting sites). Within the timescales of the project, it was not possible to estimate the emissions for the bioaerosol study undertaken. Therefore, the model results were normalised by the highest measured concentration. This allowed an assessment of the downwind decay and the sensitivity of results to the use of deposition parameters in the modelling.

The following conclusions can be drawn:

- In some cases, the observed decay is more consistent with modelling results when deposition is taken into account. However, this is primarily the case for the very upper end of the particulate size range i.e. 100 μm . It may be that using a particle size in the range 10 - 100 μm is appropriate.
- For the very large particle size (100 μm), the impact of gravitational settling outweighs the buoyancy and initial momentum effects in ADMS, but the converse is true for AERMOD.
- The choice of source type appears to be much less important than whether or not deposition and plume rise are allowed for.

In order to improve and standardise the approach to dispersion modelling of bioaerosol emissions, more information is required relating to the physical processes that occur when the pollutants disperse. For example, estimates of particle sizes and rates of coagulation are required in order to model deposition.

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1 INTRODUCTION

An increasing number of regulated sources have complex geometries near or at ground level. Common agricultural examples of these include pig and poultry farms, where emissions of ammonia and particulates are often high from sheds containing intensively farmed animals, and also from litter and manure storage, and land spreading. Other non-point sources are composting sites where bio-waste such as that contained within windrows emits fungi and bacteria. These sources are usually in rural areas which may be close to designated SSSIs, where pollutant concentration and deposition is of particular concern. In addition, agricultural and composting facilities are sources of odour, so when these are located close to residential properties, the impact of emissions must be regulated. When pollutant and odour emissions exceed screening levels, detailed modelling is required using dispersion models that account for the variations in meteorology and dispersion in the near-field. The sources of emissions are often not simple 'point' sources in the sense that their emissions are released from a single location with well-defined efflux conditions being released from a stack. Instead, they may comprise a series of small point sources, for example fan vents at the sides of buildings, where exit conditions are not well defined, or the source of emission may have a large geometry, for example a windrow or slurry lagoon. In contrast to point sources, for which there has been extensive model evaluation published in the literature, the use of non-point sources such as line, area, jet and volume sources to model agricultural and bioaerosol emissions is relatively poorly quantified from a dispersion modelling perspective. This is both because the sources usually have poorly defined physical characteristics and because the emissions are usually highly uncertain. The purpose of the current study is to improve the understanding of dispersion modelling of near-ground non-point sources.

The dimensions of non-point sources are usually defined as a series of points contained in a single horizontal plane, with additional information relating to the source height and depth where necessary: line sources have two vertices, in addition to the line width and a height above ground; area sources have three or more vertices and a height above ground; volume sources also have three or more vertices, as well as the height of the source centre, and the source depth; and jet sources are defined as a single point in three dimensions, with the source exit parameters distinguishing them from point sources.

One non-point source type that has been the topic of numerous studies is road traffic emissions, because traffic is the primary cause of air pollution in urban areas. Traffic emissions are usually approximated by a line source with increased vertical mixing, or a passive volume source where the depth represents the initial spread caused by vehicle induced turbulence. When modelling road traffic in built-up areas, buildings adjacent to roads complicate the dispersion process, with the wind at ground level in 'street canyons' flowing in the opposite direction to the prevailing wind. Traffic sources are discussed in this report, but are not considered in detail.

The first stage of this project was to undertake a review of relevant published literature including: guidance documents relating to current practice; non-point source dispersion model evaluation studies; and documents detailing field campaigns where datasets that may be of use for model evaluation purposes have been collated. Whilst non-UK examples have been considered, the majority of the literature reviewed has been from the UK.

Some general documents that give guidance relating to dispersion modelling from all source types are discussed, specifically: the Environment Agency guidance documents (H1 Annex B and Annex F), Defra's Technical Guidance TG(09), the UK ADMLC guidelines published in 2004, the US Environmental Protection Agency Guideline on Air Quality Models Appendix W document and the Institute of Air Quality Management odour guidance. These documents are relevant when considering non-point sources as many aspects of general dispersion modelling apply equally to point and non-point sources.

A range of published documents relating to naturally and mechanically ventilated agricultural sources has been reviewed and tabulated. Documents of particular interest have been discussed in detail in the text, and further tables presenting how different agricultural sources have been represented in the studies are given. By inspecting these documents, it has been possible to summarise the range of source parameters that are used as input to models when attempting to represent agricultural sources in dispersion models; these parameter ranges inform the choice of parameters used in the modelling work undertaken in this project. Documents relating to biofilters for biowaste processes and open composting windrows have been reviewed in the same way, again concluding with a summary of dispersion modelling parameters that the literature suggests are appropriate for modelling bioaerosol sources. Further, the literature review identified measurement datasets that would be appropriate for use as case studies, in order to demonstrate the models' ability to represent dispersion from non-point agricultural and bioaerosol sources.

Traffic sources are usually modelled as line or volume sources. The additional complexities associated with modelling traffic have been discussed, specifically: the non-linear aspects in terms of vehicle induced turbulence and NO_x chemistry, complexities related to modelling in urban areas, and uncertainty in emissions (exhaust and non-exhaust). Traffic sources have not been used in any of the modelling exercises undertaken during this project, but two relevant documents have been referenced.

Dispersion models have limitations and there are uncertainties that relate to model formulation and inputs. Some of these limitations and uncertainties apply to all types of dispersion modelling, for example uncertainties in meteorological data, but there are particular issues associated with modelling non-point sources. Many agricultural emissions are modelled using non-point sources because the location of the emissions is not well defined, for example, pollutants may disperse from a leaky shed, or a composting windrow. Buildings containing intensively farmed animals are ventilated using a range of mechanisms. Roof vents are usually modelled as point sources on a building, but side vents are

more complex both due to their orientation as well as the complexity of the flows in the 'alleyways' between sheds and the shed wakes. Shed ventilation rates vary with the number of animals contained within the building, the stage of the growth cycle and the ambient temperature; sheds must remain sufficiently cool to encourage efficient crop growth and CO₂ levels must not become too high, but it is too costly for the farm operators to use excessive ventilation. Consequently, ventilation rates vary, often automatically, and it is unrealistic for a dispersion modelling scenario to allow for precise variation in exit parameters. Further, in the majority of cases, exit fan concentrations are unknown and emission rates are calculated using standardised emission factors and estimates of the number of animals. Assumptions must therefore be made regarding both the magnitude of the emissions as well as the source location and efflux parameters. Source definition and emissions relating to bioaerosol sources are even more uncertain.

Many local dispersion models have been extensively validated for point sources, and these exercises demonstrate that, in general, models may perform reasonably well in moderately flat terrain when there are no buildings in the vicinity of the source, but 'real world' terrain and buildings generate complex, turbulent flow fields that are more challenging to model for the commonly used Gaussian-type plume dispersion models such as ADMS and AERMOD. Model performance and limitations associated with modelling non-point sources are discussed.

The main limitations and uncertainties of modelling agricultural sources, biowaste processes, composting facilities and road traffic emissions have been summarised using a risk-assessment approach.

There are many dispersion models that can be used to model the source types of interest for this study: agriculture, biowaste and traffic. Over 20 dispersion models have been reviewed and summarised in terms of: the source types they are able to model; whether the model is open source, proprietary or a research tool; if the model is suitable for this study; if the model has been used in this study; and the reason for rejecting the model (if applicable). The authors were interested in assessing model performance from a wide range of models, but project constraints restricted the models to those most commonly used in the UK for agricultural and biowaste modelling i.e. ADMS and AERMOD.

ADMS and AERMOD have similarities in basic approach. They are both 'new' generation models that use the Monin-Obukov similarity theory to parameterise structure of the boundary layer, and they use a quasi-Gaussian plume dispersion formulation. Both models have area, line and volume non-point source types; ADMS also has a jet source type, while AERMOD is able to model jets, but only in the form of horizontal, wind-aligned sources. Despite the similarities between the models, there are many differences in the model formulations which result in differences in model outputs. The differences between ADMS and AERMOD model performance with regard to standard point source dispersion, dispersion in complex terrain and in the vicinity of buildings is well documented, but the differences when non-point sources are modelled are less well known. The ADMS and AERMOD model formulations are discussed in detail in this report, in terms

of source descriptions, standard model features (including plume rise, deposition and meteorology) and advanced model options. The differences between the models' approach to building effects are discussed in detail. Following the detailed description of the model formulations, particular drawbacks and limitations of the models relating to modelling agricultural and bioaerosol sources have been discussed.

A series of idealised modelling scenarios have been conducted using ADMS and AERMOD. Two sets of source configurations have been modelled: one representing a 'typical' agricultural source, and one a 'typical' windrow. The parameters for these 'typical' source types have been derived from those values found in the literature. Predicted model concentrations downwind from the source have been compared for single meteorological conditions. Scenarios modelled include varying source height and orientation, efflux parameters (exit temperature and velocity) and meteorological conditions. Annual and maximum concentrations have been calculated and compared at varying distances downwind from the sources. A detailed comparison of annual average and maximum concentrations at 100 m downwind of all source types has been presented, which allows conclusions to be drawn regarding how the different non-point source types behave, and also what the differences are in near-field ADMS and AERMOD predictions.

All datasets obtained for use as model evaluation case studies included data for more than one site. Specifically, the Sniffer dataset provides data relating to ammonia, PM₁₀ and odour measurements at two farms: Whitelees and Glendevon. The Defra poultry dataset contains PM₁₀ and PM_{2.5} measurements at eight farms and the Defra bioaerosol dataset has data from four composting facilities. Four case studies were selected, as project constraints did not allow modelling to be performed for all sites. Whitelees was selected as the superior site from the Sniffer dataset as continuous ammonia measurements were made; two broiler farms were selected from the Defra poultry dataset, both using tunnel ventilation, and one also using an emissions abatement system (a baffle); and one of the composting facilities, where this site was recommended as the most robust in terms of measurements by the dataset providers.

Allowing for the differences between the studies, the modelling for each of the four cases have been approached in a consistent way. Firstly, an overview of the measurement data has been presented. Full details of measurement equipment and other site details have not been given; case study documentation has been referenced where possible, although for all studies additional data and/or documentation have been provided to the authors that is not currently in the literature. The model set up has then been discussed, including figures showing the model configuration for both point and non-point sources and tables presenting source parameter ranges. Model results are presented statistically where possible (specifically for Whitelees where sufficient ammonia measurements have been made) and graphically for other cases; the results have been discussed on a site by site basis.

The findings of the literature review, idealised scenarios and case studies have been discussed in the last chapter of this report. A discussion section puts the work in context, followed by a concise list of conclusions that can be drawn from the work undertaken. Some suggestions for good practice when modelling using non-point sources are given and these recommendations have also been presented in a flow chart format. Finally, a list of recommendations for further work has been compiled as there are many aspects of this work that would benefit from further study.

2 TASK 1: LITERATURE REVIEW

2.1 Overview

A literature review of published studies on the modelling of non-point sources has been undertaken. The focus has been on source types typical of naturally and mechanically ventilated animal sheds, biofilters for biowaste processes and open composting windrows; some discussion relating to the dispersion of traffic emissions has been included. Guidance documents, including non-UK examples, previous model inter-comparison papers and reports, and specific case studies have been reviewed. Section 2.1 presents the results of the literature review.

Dispersion modelling is not an exact science. That is, not only are there significant uncertainties associated with the inputs to the models in terms of emissions and meteorology, but also there are observational error margins in terms of the pollutant measurements. These uncertainties are in addition to the limitations of the models themselves in terms of the challenges related to modelling complex atmospheric processes in real-world situations, for instance flow and dispersion in the vicinity of buildings. The limitations and uncertainties in dispersion modelling in general are discussed in Section 2.3, with particular emphasis on modelling non-point sources. An attempt to classify the uncertainties associated with dispersion modelling of this type has been made, using a 'risk-assessment' approach.

Section 2.3 discusses a wide range of dispersion models that may be suitable for use in modelling non-point source emissions from agriculture, composting or traffic sources. These have been assessed in terms of their appropriateness for use with this project. Ten models were selected as potentially suitable for modelling agricultural and bioaerosol sources, and five for traffic. The scope of the project limited consideration to a subset of these models for use in the idealised modelling and/or case study work. Specifically, only ADMS and AERMOD have been selected to be used for the idealised modelling and case study work; Section 2.4.1 gives details of the differences and similarities between these models in terms of: source descriptions; model features; and drawbacks and limitations. Although restricting this part of the study to only two models, these are the most commonly used dispersion models for this type of modelling in the UK.

The detailed literature review that has been undertaken for this project has allowed a parameter space of source parameters to be compiled in terms of source dimensions and efflux values. This parameter space is discussed in Section 2.5. The literature review highlighted a relatively large number of datasets that were potentially useful for validating the chosen dispersion models, the majority of which proved very time-consuming and challenging to obtain. This is discussed further in Section 2.6, where the final choice of datasets is summarised.

2.2 Review of published studies

The review of published studies focuses on the different non-point source types, and each has been discussed separately: literature relating to naturally and mechanically ventilated agricultural sources are discussed in Section 2.2.2, biofilters for biowaste processes and open composting windrows in Section 2.2.3 and traffic emissions in Section 2.2.4. These sections include not only brief discussions of the documentation, but also tables indicating whether or not the documents are suitable in terms of guidance for dispersion modelling. In addition, there are a number of guidance documents that comment on the dispersion of emissions from non-point sources more generally. These are discussed in Section 2.2.1.

2.2.1 General guidance documents

The Environment Agency (EA) guidance describes the requirements for submitting an application for a permit under the EA Environmental Permitting Regulations. H1 Annex F – Air Emissions Guidance (EA H1 F, 2011) gives information relating to modelling emissions to air and H1 Annex B (EAH1 B, 2011) gives information regarding applications related to intensive farms; EA H1 B refers to the guidance given in EA H1 F for the specific case of modelling air emissions from intensive farming. Further, EA H1 F refers to the use of AERMOD and ADMS for modelling of emissions to air from these source types.

Defra's Technical Guidance document TG(09) (LAQM.TG, 2009) is aimed at helping local authorities perform their Review and Assessment duties, which are required as part of Local Air Quality Management (LAQM). The guidance document discusses emissions, monitoring and modelling relating to air pollutants. This guidance document is primarily concerned with traffic emissions as these cause the majority of air quality problems in urban areas.

The UK Atmospheric Dispersion Modelling Liaison Committee (ADMLC, 2004) guidance document describes current ADMLC guidelines on dispersion modelling. ADMLC (2004) outlines a general procedure relating to selection of a model; recommends the use of different models when possible; and discusses, in general terms, requirements relating to sensitivity testing and model uncertainty. The document does not contain a formal list of recommended models. Further, the uncertainty of source types for ill-defined emissions such as those from agricultural sources and biowaste processes, of relevance to the current study, is not discussed.

The current[†] US Environmental Protection Agency Guideline on Air Quality Models document (US EPA, 2005) describes how pollutant emissions in AERMOD may be modelled as point, line, area or volume sources (Sections 8.1.1. and 5.2.2.2e). Line sources are typically used to model traffic and lines of roof

[†] Appendix W is currently under review

vents, for example from pig and poultry housing. This document recommends that area or volume sources are used to model minor sources with small emissions that cannot practically be modelled as point sources; for example, fugitive dust emissions are represented using volume sources.

The Institute of Air Quality Management odour guidance (IAQM, 2014) presents the current suggested approach to modelling sources of odour. IAQM (2014) notes that it is often difficult to model odour sources because emissions can be diffuse, fugitive, and/or intermittent; the guidance document recognises the need to collate more information concerning dispersion model performance. IAQM (2014) recommends that an odour source should have well-defined source characteristics that are not subject to large variation; further the model domain must not include other relevant odour sources which are difficult to model. Composting sites are highlighted as being particularly difficult to define because, for instance, the turning of windrows leads to peaks in the source emission rate. They note that an appropriate choice of point, line, area, or volume sources may be used to model odour sources; for example aeration tanks are modelled as area sources with zero or minimal exit velocity.

2.2.2 Agricultural sources

Table 1 summarises the literature that has been reviewed in order to assess the current status of modelling emissions from naturally and mechanically ventilated agricultural sources. Further, the information given in these papers and reports has been inspected in order to:

- Classify the range of appropriate source parameters for modelling agricultural sources that should be used for the idealised modelling (Task 2); and
- Identify datasets that can be used as case studies for demonstrating dispersion model performance (Task 3).

A selection of these papers will be discussed in detail in the following paragraphs.

Demmers *et al.* (2009, 2010) describes a Defra-funded study in which emission rates from poultry sheds were monitored alongside in-house concentration measurements of PM, ammonia (NH₃) and bioaerosols. The effect of abatement systems was examined. Most relevant to this study was the measurement of PM₁₀ and bioaerosol concentrations downwind of the poultry sheds. Concentrations were found to be at background level at around 100 m downstream and bacterial and fungal composition was typical for agricultural areas. PM₁₀ and viable bacterial counts were measured 50 m upwind of the source, at the source location, and at downwind distances of 50 m, 100 m, 200 m, and 350 m. The results are presented separately based on the farm type; i.e. for broilers, caged egg layers and free range houses. A total of eight farms were examined as part of this study.

Table 1 Naturally and mechanically ventilated agricultural sources studies

Reference	Model evaluation study	Suitable for guidance	Comments
Winges, 1991			This is the user guide for the US EPA Fugitive Dust Model; passive point, line or area sources can be modelled using this tool.
Seedorf, 1998			Description of a measurement campaign recording the concentration of airborne endotoxins and microorganisms in livestock buildings (cattle, pig, poultry) in England, The Netherlands, Denmark and Germany.
Sheridan <i>et al.</i> , 2004			ISCST3 was used to model odour nuisance from a pig farm in Ireland; abatement techniques are assessed (including biofilters); no model evaluation was presented.
Theobald <i>et al.</i> , 2006	✓		CEH report on the initial development of SCAIL Agriculture
Curran <i>et al.</i> , 2007	✓		Evaluation of ISC3 and CALPUFF for modelling odour nuisance from a pig farm in Ireland. Both models gave similar results. Source type is unclear.
Schulte <i>et al.</i> , 2007	✓		AERMOD odour study from four pig houses (discussed in text)
Demmers <i>et al.</i> , 2009			Defra project report relating to a study of dust and ammonia emissions and concentration in the vicinity of several poultry farms including broiler farms, caged layers and free-range birds. There is some discussion of abatement techniques (discussed in text).
Schewe and Smith, 2009			Fugitive emissions are modelled using AERMOD and ISCST3. The choice of source type (volume or area) and source dimensions are investigated, as is the impact of key meteorological parameters. Authors concluded that volume sources always give higher concentrations than area sources.
Theobald <i>et al.</i> , 2009	✓	✓	SCAIL Agriculture paper (discussed in text)
Demmers <i>et al.</i> , 2010			Paper relating to Demmers, 2009 study (discussed in text)
Theobald <i>et al.</i> , 2010	✓		Dispersion model intercomparison study (discussed in text)
UK Environment Agency AQMAU, 2010		✓	UK Environment Agency Air Quality Modelling and Assessment Unit guidance on modelling ammonia emissions from agricultural sources (discussed in text)
Wichink Kruit <i>et al.</i> , 2010			This a scientific paper discussing a model for the surface-atmosphere exchange of ammonia, including the effects of stomatal resistance and such like; i.e. it is concerned with the technical scientific aspects of ammonia deposition.
D'Abreton, 2011		✓	This document details best practice for modelling odour nuisance of meat chicken farms for the Queensland (Australia) poultry industry. It includes discussion of AUSPLUME, CALPUFF, TAPM and AERMOD. The authors give a recommendation to model ventilated chicken sheds as low velocity buoyant point sources to adequately take account of plume rise.
Hill <i>et al.</i> , 2014	✓	✓	SCAIL Agriculture report (discussed in text)

In 2010, the Environment Agency Air Quality Modelling and Assessment Unit (AQMAU), published a general guidance document on modelling the air concentration and deposition of ammonia emitted from intensive farming (EA AQMAU, 2010). Table 2 below gives details of the different agricultural source types considered and the recommended modelling approach in terms of usage of point, line or volume sources. The guidance includes a brief discussion of the various uncertainties relating to modelling emissions from agricultural sources.

Table 2 Agricultural sources modelling summary from EA AQMAU (2010)

Real-world source description	Source type	Additional source information	Comments from guidance document
Sheds with roof vents	Elevated point sources	Model building	
Sheds with large number of roof vents	Composite point sources	Model building	Use stack diameter and exit velocity of individual vent but mass emission rate of composite source.
Sheds with tunnel ventilation with long line of gable-end fans or if shed is wide	Low level line source		Low level source accounts for building downwash effect
Sheds with tunnel ventilation with gable-end fans; shed is not wide and line of fans is not long.	Series of point sources	Model building	
Naturally-ventilated shed	Volume source		
Naturally-ventilated shed with side inlets and roof exit	Option A: Low level line source		
	Option B: Series of point sources		
Side vents which direct the air flow to ground level	Option A: Series of ground level point sources	Source height zero	
	Option B: Line source		
Free-range animals	Not specified		Apply time-dependent emission factor between free-range area; conservative assumption: all emissions from housing

This guidance document outlines a two-stage approach for modelling ammonia deposition, specifically:

- With an appropriate dispersion model, calculate annual average ammonia air concentrations with the deposition module switched off; allow for buildings and terrain where appropriate. Calculate the dry deposition flux as the product of the ground level concentration and the deposition velocity.

- If the relevant assessment thresholds are exceeded, re-calculate the dry deposition flux using the spatially varying deposition module in ADMS[‡].

Five years of meteorological data should be used in these assessments.

Theobald *et al.* (2010) presents an intercomparison of models commonly used for simulating dispersion of agricultural ammonia, including ADMS, AERMOD, LADD (Hill, 1998) and OPS-st (Van Pul *et al.*, 2008). This paper is of particular interest to the current study because whilst ADMS, AERMOD and OPS-st have similar Gaussian plume formulations, LADD is a Lagrangian vertically-averaged air column model. The models were evaluated with data from two case study farms in Denmark and the USA. There are significant differences between all models, but the models perform best when the sources are modelled as ground-level sources. All models, with the exception of LADD, are found to be acceptable by a defined statistical measure. Four scenarios were considered in the study: a slurry lagoon, a slurry tank, naturally ventilated livestock housing and artificially ventilated livestock housing. The modelling approach used for each of these scenarios is outlined in Table 3 below.

Table 3 Agricultural sources idealised modelling summary from Theobald *et al.* (2010)

Real-world source description	Source type	Additional source information	Comments
Slurry lagoon	Area source	Ground level, 20 m x 20 m, exit velocity 0.1 m/s	Models perform similarly
Slurry tank	Area source	Source height 2 m, exit velocity 0.1 m/s	Models perform similarly
Naturally ventilated housing	Volume source	Source height 0 – 2.5 m	ADMS lower concentration in the far field
Artificially ventilated housing	Point source	Source height 5 m, ambient release, 0.5 m stack diameter, exit velocity 0.1 m/s	All models differ

Schulte *et al.* (2007) present results of using AERMOD to model odour from four pig houses. Point, line and volume source types were used. Source information is summarised in Table 4. The point source was found to perform best with volume and area sources giving similar results that significantly under-predicted the concentrations.

[‡] EA AQMAU (2010) specifies ADMS version 4.2, but the current version of ADMS that includes the spatially varying deposition module is ADMS 5.1.

Table 4 Agricultural sources modelling summary from Schulte *et al.*, 2007

Real-world source description	Source type	Additional source information	Comments
Pig houses	Point source	11 m – 12 m effective diameter, exit velocity 0.01 m/s, exit temp 25 °C, buildings modelled	
Pig houses	Volume source	Source height varies over source 2.4 m – 4.6 m, source 13 m across, 1.1 m high	Varying source height has little impact on results
Pig houses	Area source	Source dimensions 58 m x 12.5 m	

The SCAIL Agriculture Tool (Theobald *et al.*, 2009) was developed as a screening tool for atmospheric concentration and dry deposition at the nearest edge of a sensitive ecosystem downwind of a source of ammonia. The SCAIL-Agriculture model was first developed by the Centre for Ecology and Hydrology (CEH) for the Environment Agency (EA). The model was subsequently modified for the Scottish Executive with the aim of providing a screening tool able to help the Scottish Environment Protection Agency (SEPA) assess permitting and planning applications (v2.0). The model is used by environmental regulators throughout the UK to assess the impacts of agricultural installations on designated habitats including Habitats Directive sites and designated sites under National Legislation (SSSIs /ASSIs/NNRs). The objective is to screen environmental permit applications from farm units and to assess impacts from agricultural developments applying for planning permission to determine if there is the possibility of adverse impacts; if such impacts are found, more detailed dispersion and deposition modelling is required, for instance using ADMS or AERMOD. The tool was updated in 2014 (Hill *et al.*, 2014) to model PM₁₀ and odour.

The SCAIL-Agriculture Tool incorporates AERMOD and makes assumptions regarding source properties based on data entered by the user. Table 5 summarises the agricultural pig and poultry sources represented in the tool, the AERMOD source types used and the information the user is required to enter.

Table 5 Source types represented in the SCAIL-Agriculture Tool

Source description (pig or poultry)	Source used in SCAIL Agriculture Tool	Additional source information required
Housing	Point source with a building	Ventilation type, building height, fan location (in terms of roof or side of building), fan exit parameters, number of animals, housing floor area and livestock cycle stage.
Litter / manure storage	Area source	Weight, area and type of litter / manure.
Land spreading	Area source	Weight, area, years of application and type of land spreading.

The Sniffer SCAIL Agriculture Update report (Hill *et al.*, 2014) contains a large catalogue of studies giving measurements of agricultural ammonia

concentrations, deposition and odour measurements that could be used for model evaluation studies for the SCAIL-Agriculture tool. The most robust studies have been identified by the authors of that study. The report presents information relating to a wide range of agricultural sources where monitoring has been undertaken; examples of these studies are given in Table 6, alongside the source information specific to each study.

One of the conclusions of this report was that there were few robust datasets available with reliable measurements of source emissions and concentrations, with associated detailed meteorological measurements which could be used for model evaluation. As a consequence, Sniffer carried out their own ammonia, PM₁₀ and odour monitoring campaigns at two sites in Scotland: Whitelees and Glendevon; the data from these studies are recent and robust. Sniffer used these datasets as model evaluation studies to calibrate SCAIL-Agriculture and also modelled the sites using AERMOD.

Table 6 Agricultural sources modelling summary from Hill *et al.*, 2014

Real-world source description	Additional source information
Broiler shed with fans	Source and building height 6.4 m, diameter 1 m, exit velocity 7.8 m/s
Naturally ventilated shed	Source and building height 5.9 m
Broiler shed with fans	Source and building height 4.5 – 5.0 m, exit velocity 1.0 m/s
Pig shed	Source height 3.5 m, building height 7.0 m, diameter 1 m, zero exit velocity
Layers shed	Source and building height 7.0 m, diameter 1 m, exit velocity 1.9 – 6.6 m/s
Shed with fans	Source and building height 6.4 m, diameter 0.8 m, exit velocity 3.3 m/s

2.2.3 Bioaerosol sources

Table 7 summarises the literature that has been reviewed in order to assess the current status of modelling emissions from biofilters for biowaste processes and open composting windrows. Further, the information given in these papers and reports has been inspected in order to:

- Classify the range of appropriate source parameters for modelling bioaerosol sources that should be used for the idealised modelling (Task 2); and
- Identify datasets that can be used as case studies for demonstrating dispersion model performance (Task 3).

A selection of these papers will be discussed in detail in the following paragraphs.

Williams *et al.* (2013) presents evidence relating to bioaerosol emissions and dispersion from composting facilities with a view to providing guidance and informing policy for the regulatory bodies; this work was funded by Defra. A comparison of measurements of bioaerosols at composting sites obtained from a variety of methods is presented. Spatial and temporal variations in bioaerosol concentrations were also measured. Work was undertaken to establish whether

odour is a marker of bioaerosol exposure. The report therefore contains a variety of measurements and measurement techniques of odour and bioaerosol concentrations at composting sites and biowaste facilities. Four representative composting facilities were selected, of various sizes, including open windrow sites and fully-enclosed sites. Meteorological data were recorded, as were site activities. Dispersion modelling was performed for the site where odour measurements were made. The report notes that concentrations above levels defined by legislation as being acceptable are rare beyond 250 m and that there is no evidence of a seasonal pattern in bioaerosol concentrations; also that the measurements are sensitive to the technique used – some devices perform better when concentrations are high and vice versa. No relation was found between odour and bioaerosol concentration. The report concluded that there is very little confidence in the bioaerosol and odour emission rates which are very hard to ascertain and can vary by orders of magnitude depending on the site activity.

Douglas (2013) is a PhD thesis that looked in detail at modelling bioaerosol emissions from open windrow composting facilities; the study used the ADMS dispersion model and the conclusions included a number of best practice modelling recommendations. Specifically, when using ADMS to model bioaerosol sources:

- The wet and dry deposition, and buildings options are not used
- The source is represented as area, with geometry representing the size of a compost windrow on the site being modelled
- The emission rate is back-calculated to correspond proportionately to measured bioaerosol concentration measurements
- A source height of 2.65 metres is used
- The pollutant exit velocity and pollutant temperature used is 2.95 m/s and 29°C respectively
- The background concentration option is used
- Good quality meteorological data is used, preferably collected on the composting facility that is modelled
- The surface roughness, grids options and any additional options, such as 'CALMS' is based on information from the meteorological file

The exit velocity value of 2.95 m/s recommended for use in this work is considerably higher than suggested values found elsewhere. The value was obtained by investigating the parameter space for the efflux parameters and finding the values that gave the best fit to measured data. The author suggests that the combination of exit velocity and temperature are likely to represent the *average* efflux parameters between: intermittent high concentration releases caused by agitation activities; and continuous low concentration releases from non-agitated compost.

Table 7 Biofilters for biowaste processes and open composting windrows studies

Reference	Model evaluation study	Suitable for guidance	Comments
Swan et al, 2003	✓	✓	The Composting Association and Health and Safety Laboratory for the Health and Safety Executive report including a literature review of bioaerosol studies related to composting facilities. The main purpose is to identify risk to human health, especially workers, but also to neighbouring environment and residents. Includes a review of modelling and some comparison of modelled to monitored concentrations. The authors recognise the problem of large uncertainty in emission rates.
Pollard et al, 2004	✓		EA environmental risk management framework for composting facilities in England and Wales, of interest primarily as a first step toward regulatory guidance of composting facilities; contains an example dispersion model for a biofilter, but in this case it is for a standard vent or stack emission from a building and does not include composting source types that are harder to model, e.g. open windrows.
Composting Association, 2004			This report suggests that the standard receptor for regulatory concentration assessments should be located at 250 m downwind of the site; also that measurements should be made at 25 m upwind and 200 m downwind with Andersen samplers and that 'the rule of thumb' is for applications not to exceed 1000 CFU/m ³ bacteria.
ADAS/SWICEB, 2005	✓		Includes measurements of bioaerosols and odours from range of composting facilities. Includes some comparison of modelled concentrations to measurements at 2 sites (2 different composting systems). The modelling uses ADMS and the source type used is an area source.
Drew et al, 2006			Bioaerosol concentration data measured at a composting facility was analysed by a series of model experiments. The paper is a first step in trying to establish best practice for modelling bioaerosols. There is no direct comparison of modelled concentrations to measured concentrations but a series of model experiments were carried out to investigate the nature of bioaerosol dispersion; the authors note here that dispersion models cannot account for the coagulation of the particles. In this study bioaerosol sources were modelled as either point or area sources using ADMS.
Scaife et al, 2008			UK Environment Agency report about bioaerosol emissions at agricultural sites and the potential impact on human health. The report finds that most studies concerning bioaerosols deal with emissions/health effects within buildings and that there are few studies on bioaerosol emissions from agricultural sites.
CERC, 2009			Report describing the modelling of a composting facility, including open windrows, in Northamptonshire. As is typical for bioaerosol modelling from composting facilities there was significant uncertainty in the model input parameters. The open windrows were

Reference	Model evaluation study	Suitable for guidance	Comments
			modelled as area sources, though sensitivity testing showed that there was little difference when they were modelled as volume sources. Shredding of waste was modelled as point sources. For the open windrow low exit velocities of 0.2m/s were used and a constant efflux temperature of 35°C was used. Time-varying factors were used to take account of the varying activities on site; a conservative approach was taken in order to address the uncertainty.
Stagg et al, 2010			This report contains details of bioaerosol sampling at six representative waste composting sites in the UK. Sampling was linked to specific site activities and samples were collected from close to the source. Measurements of bioaerosol dispersion were taken at downwind locations up to 250 m. An upwind measurement was also taken to estimate the background concentrations. Each site was visited in the summer and the winter to investigate any possible seasonal variation in bioaerosol emissions.
Pankhurst et al, 2011			Report giving measurements of spatial variation of microorganisms and endotoxins around composting facilities.
Douglas, 2013	✓	✓	PhD thesis on bioaerosol emissions from open windrow composting facilities (discussed in text).
Frederickson et al, 2013	✓		A critical scientific review from the Environment Agency looking at the effectiveness of biofilters at odour or bioaerosol removal. It includes fieldwork from two sites and a case study looking at an odour assessment at a composting site, but the focus of these is on the source emissions of odour and bioaerosols, rather than looking at concentrations downwind from the site.
Williams et al, 2013			Description of results from a Defra-funded study into bioaerosol and odour emissions from composting sites. The study includes measurements of bioaerosol concentrations in the vicinity of four composting facilities (discussed in text).
Wéry, 2014		✓	Review paper on microbial diversity in bioaerosols from composting facilities including a review of the methodologies used in investigating bioaerosol dispersion. There is some discussion of: modelling and the difficulty of specifying the source emission due to the huge variation in the activity-dependent emission rate; and the importance of allowing for the formation of agglomerations of bioaerosols as they disperse.
O'Connor et al, 2015			Paper presenting a new technique for measuring bioaerosols and a case study for the new technique has been performed at a composting site. Of interest to the present work, it shows that bioaerosol counts vary enormously depending on the site activity and the weather, particularly the wind speed.

2.2.4 Traffic sources

A traffic source is almost always considered as a continuous stream of vehicles, and as such is represented in dispersion models as a long, thin source, most commonly a line or volume source. The width of the source corresponds to the road or carriageway width (more than one carriageway may be considered in some models) and the depth represents the vertical height at which the exhaust is released, as well as some representation of the initial mixing of the exhaust in the vehicle wake. In the mid to far field, it makes negligible difference if the source is represented either as a line source with an initial vertical spread or a volume source that uses a top-hat profile to represent the initial vertical mixing. The buoyancy and momentum of traffic exhaust is rarely considered in the most commonly used dispersion models; this is a reasonable assumption except in light wind, stable conditions or where vehicles are stationary, where the emissions may be subject to plume rise.

The relationship between road traffic emissions and pollutant concentrations is non-linear to a variable extent for a number of reasons. Vehicle induced turbulence acts to decrease ground-level concentrations as traffic volumes and speeds increase (Stocker *et al.* 2005); exhaust NO and NO₂ react with ozone in fast, non-linear photolytic chemical reactions; and for some pollutants, deposition is important. Some simple screening (for example DMRB) and more advanced (for example CALINE) dispersion models neglect the non-linear aspects of dispersion from road traffic; for pollutants that do not undergo significant chemical reactions, this simplification is reasonable, but when detailed near-road modelling is undertaken non-linear aspects should be accounted to some extent.

City morphology causes greater inhomogeneity in the wind flow compared to rural areas with moderate terrain. The prevailing wind flow within the boundary layer is displaced above densely packed buildings; the height of this displacement is related to the average building height on a neighbourhood scale. When buildings form street canyons, the wind at street level may flow in a direction opposite to the prevailing wind; further winds may be channelled along streets. In residential areas, noise barriers are increasingly common; these act not only to reduce noise levels in the vicinity of busy roads, but also reduce pollutant concentrations by elevating the traffic source plume over the barrier. In order to best model local-scale urban dispersion, it is important to allow for these complex flow variations; the near-road source dispersion models available account for some of these features (ADMS, OSPM, RLINE).

The emission factor datasets available in the UK for use in road source dispersion modelling are a combination of detailed fleet and emission factor data. However, despite road traffic emissions being a relatively well-studied area of research, for some pollutants, there appears to be an inconsistency between the emission factor databases that are derived from emissions factors supplied by vehicle manufacturers, and those measured by, for example remote sensing equipment. Carslaw *et al.* (2013) presents measured NO_x/CO₂ and NO₂/CO₂ ratios that differ greatly from those included in the COPERT emissions tool, particularly for diesel vehicles. One of the primary reasons that the measured NO_x emissions differ

from the manufacturer's values is that engine efficiency (and hence emissions) is related to the driving conditions. In stop-start congested traffic and near junctions, drivers frequently accelerate and brake; the most commonly used emission factors in the UK are based on an average speed, and a 'typical' urban drive cycle, which may not be representative of real-world conditions. Increasingly, other European countries use emission factor datasets that account for different driving conditions, for example the HBEFA emissions model developed by the Environmental Protection Agencies of Germany, Switzerland and Austria. Recently, Highways England has published a dataset (IAN 185/13) that includes NO_x, PM₁₀ and CO₂ factors appropriate for use in motorway and non-motorway driving conditions categorised into: heavy congestion, light congestion, free flow and high speed.

Road traffic sources can be modelled at a range of scales, depending on the required resolution of modelled concentration data. A single road segment may be many 100s of metres, along which it is assumed that the traffic speed and flow remains constant, at least on an hourly basis. This approach is appropriate for relatively low resolution modelling over a few kilometres. Conversely, for hot spot modelling, output from microscale traffic models can be used in conjunction with microscale emissions models to calculate detailed variations in emissions that can be modelled using road source dispersion models.

Emissions from all pollutants are modelled as if they are released from the vehicle exhaust pipe. However, the non-exhaust PM₁₀ and PM_{2.5} traffic emissions component are of the order of 75% and 50% respectively of the total exhaust (see for example data provided in the London Atmospheric Emissions Inventory, LAEI, 2013). Non-exhaust emissions are usually considered as the sum of emissions from brake wear, tyre wear and road wear, in addition to a resuspended particulate component. Clearly, these components are generated over a wider area than exhaust emissions. However, neglecting this aspect of the source characterisation is unlikely to impact severely on accuracy of modelling results, particularly as there is great uncertainty associated with non-exhaust emission factors.

Dispersion modelling of traffic sources is a large area of research, with many interesting aspects. As the primary focus of the current work is to consider non-point sources from agricultural and bioaerosol sources, it has not been possible to also include idealised modelling and case studies that relate to road traffic. However, the following documents should be considered if further work is required in this area:

- Heist *et al.* (2013) is a paper that presents results from a near-road source model inter-comparison exercise between ADMS-Roads, AERMOD, CALINE 3, CALINE 4 and RLINE. The results from two case studies are presented: Caltrans Highway 99 and Idaho Falls.
- The Air Quality Modelling Steering Group (AQMSG) is finalising a document entitled 'Atmospheric Dispersion Modelling in Urban Areas at the Microscale' that discusses many of the issues associated with emissions and dispersion modelling of road traffic.

2.3 Limitations and uncertainties in dispersion modelling

The dispersion of pollutants within the atmosphere is a complex process, as illustrated by the schematic diagram shown in Figure 1. Models are able to represent the various aspects of atmospheric dispersion and the methodologies used differ from model to model in terms of formulation and complexity. The uncertainty related to using a model to predict pollutant concentrations is discussed in the literature and model output is usually subject to acceptability criteria that allow for such uncertainty.

The EA guidance document on modelling ammonia from agricultural sources (EA AQMAU, 2010) suggests that modelled results are typically within $\pm 50\%$ of measured values for the annual average concentration; this document states that estimating the deposition adds significant additional uncertainty.

There are limitations and uncertainties associated with all aspects of the modelling, consequently it is important to understand the *relative* importance of the limits and uncertainties associated with each aspect of the modelling. Further, the limitations and uncertainties differ with the type of modelling scenario. For example, there are different uncertainties associated with modelling industrial point sources compared to modelling agricultural non-point sources.

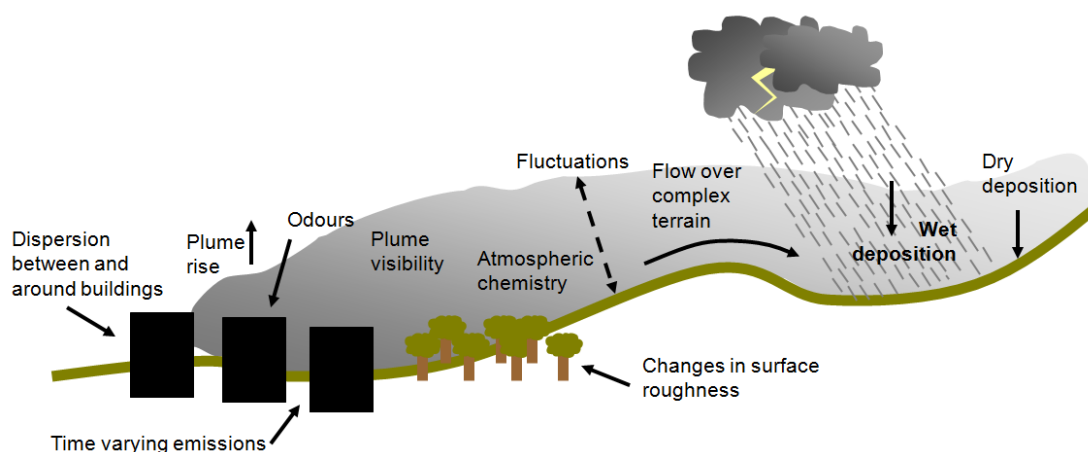


Figure 1 Schematic demonstrating complexities of dispersion modelling

The main limitations and uncertainties of modelling agricultural sources, biowaste processes, composting facilities and road traffic emissions are summarised in Table 9 using a risk-assessment approach. This is similar to the concept suggested in the AQMAU NSCA paper on model uncertainty (Shi and Ng, 2002). That is, each aspect of the modelling has been given an uncertainty classification. For some modelling parameters, this uncertainty level is related linearly, or near-linearly, with the modelled results, for instance emissions and observational uncertainty. For other parameters, the relationship between the uncertainty of a particular input parameter and the impact that it has on the modelled result is more complex, for instance meteorological inputs and model

performance. For these parameters, the uncertainty rating needs to be a combination of the uncertainty level of the model input / feature and the possible impact that an erroneous value will have on the modelled result. Finally, when discussing model limitations, it is not valid to consider the uncertainty of the model input, only the impact that a particular limitation has on the model results.

The majority of these classifications are a result of the authors' experience in modelling these source types, and as such can be considered subjective; however, where possible, references to the literature have been given to support the categorisations. Further, these tables attempt to quantify model limitations and uncertainties associated with standard modelling studies, for example for standard EA assessments and planning applications that consider annual average concentrations; they do not necessarily apply to particular case studies where shorter-term measurements may have been taken.

Descriptions of the uncertainty classifications are given in Table 8.

Table 8 Uncertainty classifications

Uncertainty classification	Abbreviation used	Estimated possible range for the impact of using an erroneous parameter on the magnitude of modelled concentrations
Low	L	< 30%
Medium	M	30% – 100%
High	H	> 100% but less than an order of magnitude
Very high	V	An order of magnitude

The values in the final column of Table 9, which presents an estimate of the overall uncertainty classification, may be either the average of the two estimates (for instance, the combination of a 'Low' and 'High' would result in a 'Medium'); alternatively, the final result may take either of the two values (for instance, the combination of a 'Medium' and a 'High' could be either 'Medium' or 'High'); this final classification is based on the authors' experience.

There are various limitations and uncertainties that apply to dispersion modelling in general. These are primarily related to:

- Emission rates

Emission rates from the most commonly modelled non-point sources are estimated using activity data combined with emission factors, rather than being directly measured emissions. For example, for poultry farms, the emission rates of ammonia and particulates are estimated from the number of birds in the shed and the stage of their growth cycle, and for traffic sources, an estimate of the number of vehicles on the road is required, together with assumptions regarding the fleet mix, and the vehicle speed. At a particular site, the agricultural activity values are usually accurate i.e. the farmer knows how many animals are present; traffic activity data are more approximate as they are estimated from

traffic models or approximations based on counts taken over a short time period. For agricultural sources, the emission factors used are relatively unrefined, whereas for traffic sources, the factors are very detailed.

The emissions from bioaerosol sources are highly uncertain. This is in part because the bio-processes are very complex and varied, so within a particular facility, there will be a wide range of bacteria; also the bio-processes are very sensitive to temperature, and composting temperature may not be known. However, the greatest uncertainty relates to the variation in emissions for the different on-site processes, for example shredding and turning; emission rates vary by orders of magnitude when these activities take place. As a result, the most reliable way to assess emissions from bioaerosol sources is to undertake on-site measurement campaigns.

The magnitude of odour emanating from a particular facility can only be reliably estimated by on-site measurements using olfactometry of internal concentrations and ventilation rate. Downwind measurements should be treated with caution due to both the influence of other sources on measurements and the reduced accuracy of olfactometry for low odour levels.

Table 9 gives suggested uncertainty ratings for the emission rates from agricultural sources (odour, ammonia, bioaerosols, NO_x and PM), biowaste and composting facilities (odour and bioaerosols) and road traffic (NO_x and PM).

- Observation uncertainty

Although it is intuitive to assume that measured concentrations are accurate, the literature suggests that there is considerable uncertainty associated with some measurement techniques. The EU legislation (EU 2008) includes uncertainty values relating to data quality objectives for ambient air quality measurements that range between 25 and 50 % for various pollutants. These measurement uncertainty values have been incorporated in the Delta tool which has been developed to assess air dispersion model performance (Thunis, 2012).

For the particular case of ammonia measurements, these should be reasonably accurate if the instrumentation has been calibrated to a sufficiently high standard.

There are various techniques used to measure particulate concentrations, for example using TEOM and gravimetric (Partisol) instruments. The uncertainty with these measurements is related to the volatile nature of some of the particulate components, which may evaporate during the measurement process (Charron *et al.*, 2004).

NO₂ diffusion tube samplers are well-known to be inaccurate. As a consequence, when observation data from these samplers are used, the

UK guidance advises that a calendar-year dependent bias adjustment technique is applied to 'correct' the data (Local Air Quality Management Technical Guidance, 2009).

The accuracy of different samplers is sometimes related to the magnitude of the observed concentration. For example, when measuring *aspergillus fumigatus* from composting facilities, IOM samplers are accurate when measuring high concentrations, but their accuracy reduces when concentrations are reduced; conversely, Andersen samplers are only accurate for moderate concentrations, as when these are used close to the source their capacity is overloaded too quickly. Other issues with measuring bioaerosols include spores dying prior to collection.

Table 9 gives suggested uncertainty ratings for the observed data for each of agricultural sources, biowaste and composting facilities and road traffic.

- Meteorology

The hourly variation of wind speed, direction and a measure of the net heat flux in the atmosphere are required to estimate the boundary layer profiles that drive atmospheric dispersion. For the purposes of this discussion, these are assumed to be measured data, although dispersion models can also be driven by data from mesoscale meteorological models. In rural areas, where the majority of agricultural and bioaerosol sources are located, if there is little change in surface roughness and terrain height these values are reasonably spatially homogeneous. Consequently, although meteorological data used as input to models may not be local to the source, the data are reasonably representative (if local effects have not influenced the measurements). Further, some models account for a change in the surface roughness between the meteorological measurement site and dispersion site.

Traffic sources are modelled within both urban and rural areas. In urban areas, the prevailing meteorological conditions are affected by the built-up nature of the area; densely packed buildings reduce wind speeds close to the ground, and street canyons created by tall buildings cause re-circulation and channelling of flow. Thus in urban areas, there is more uncertainty associated with the meteorological parameters.

'Hourly' measurements of meteorological data are not always hourly. That is, whilst the wind speed and direction are usually averaged over the full hour, the temperature, cloud cover and rainfall data are spot measurements taken at a time ten minutes before the end of the hour; consequently, the data are not truly representative of the hour. The wind direction has the most variation of all the meteorological variables used by the model, with fluctuations being related to turbulence levels in the atmosphere. The Gaussian plume dispersion models may account for this to some extent, by modelling an ensemble mean plume. Changes in wind direction are very important when a model is being used to predict

concentrations that are fixed in space and time, but when period average values are of interest, fluctuations are less important.

Table 9 gives suggested uncertainty ratings for wind speed and direction, temperature, cloud cover and rainfall observations that are commonly used to drive dispersion models.

- Source definition

The definition of agricultural and bioaerosol sources tends to be poor. For example, poultry sheds often have exit fans which can be modelled as point or jet sources, but the sheds themselves may leak emissions more generally, particularly when ventilation rates are low. The fans will be set at varying speeds depending on the temperature within the shed, and the different fans may be used independently, resulting in uncertainty relating to the source exit velocity, if point sources are being used. Poultry generate heat, which is related to the stage in the cycle, thus altering the source exit temperature. In some cases, these uncertainties in the specific source parameters motivate the use of non-point source types such as volume sources to represent agricultural emissions.

For bioaerosol sources, there is often uncertainty relating to the spatial extent of the source, in addition to source temperature information. In order to overcome such uncertainties, again volume sources are often used to represent the whole site.

If emissions from a single vehicle were to be modelled, then uncertainty relating to exit velocities and temperatures would be high. However, it is commonplace to model traffic as a continuous flow of vehicles (major roads) or vehicles dispersed over a wide area (minor roads). When aggregate vehicles are modelled, the source definition is relatively accurate, as the vehicles are known to travel along roads; in most cases, the importance of traffic-induced turbulence outweighs the influence of exhaust exit characteristics, and sources can be modelled as volume sources, or line sources with an initial plume spread that corresponds to the initial mixing height of the vehicle exhaust.

Table 9 gives suggested uncertainty ratings relating to source dimensions, exit velocities and exit temperatures.

- General model performance

When using a dispersion model, it is important to be aware of the reliability of model outputs, in the absence of uncertainties relating to the model inputs. That is, if the model configuration is such that error margins relating to meteorology and emissions are small, how reliable are the model predictions? Previous studies have demonstrated (CERC, 2015 and US EPA, 2003) that new-generation Gaussian dispersion models such as ADMS and AERMOD usually perform well in flat terrain in the absence of buildings, but that when terrain elevation is significant, and buildings

influence the flow field in the vicinity of a release, model performance reduces. In order to quantify the uncertainty relating to model performance for these scenarios, the model results must be compared to measurements.

Uncertainty associated with the meteorological and emission input parameters and the measurement data can be minimised by undertaking model evaluation exercises using data from field campaigns where the model input parameters and observational data are robust.

Results from such model evaluation exercises are generally available. For example, the US EPA undertakes field campaigns and wind tunnel studies (US EPA, 2003) to validate the regulatory industrial sources model AERMOD and its road source research tool RLINE (Snyder, 2013). In many cases, these model evaluation databases are made available not only for model evaluation of the US EPA dispersion models but also for other organisations to use. The US EPA AERMOD model evaluation databases and results are available from the US EPA website (US EPA, 2015). The majority of these studies have also been used to assess ADMS model performance, and these results are available from the CERC website (CERC, 2015).

Model intercomparison exercises are useful for assessing model performance. Many of these are presented at the series of workshops relating to the initiative on "Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes" (HARMO, 2015).

Generally, these studies demonstrate that the models perform more poorly with increasing complexity. For instance, when modelling dispersion from a single source in relatively flat terrain where there are no significant buildings present in the vicinity of the source, models give a good prediction of observed concentrations if the meteorology and emissions data are robust. However, when there are variations in terrain height, and buildings alter the near-source flow, models agree less well with observations.

Table 9 gives suggested uncertainty ratings for model performance when the model is applied to different situations, specifically: flat terrain, sources close to and influenced by buildings, regions of complex terrain and within street canyons. For the agricultural and bio aerosol sources, the uncertainty analyses are applicable to concentrations modelled outside the site boundary; for road traffic, the analyses apply to major roads in urban areas which may or may not be contained within a street canyon. Note that for these uncertainty ratings, the 'uncertainty level' classification is invalid.

Table 9 Suggested uncertainty ratings associated with modelling non-point sources *the road traffic uncertainties relate to major roads in urban areas, ^Δfor agricultural and bioaerosol sources, these categorisations apply outside the site boundary; classifications used: L – Low, M – Medium, H – High, V – Very High (Table 8).

Item	Example category	Uncertainty level				Impact of poor estimate ^Δ				Overall uncertainty rating			
		Agriculture	Biowaste	Composting	Road traffic	Agriculture	Biowaste	Composting	Road traffic	Agriculture	Biowaste	Composting	Road traffic
Emission rates	Odour	H	V	V	-					H	V	V	-
	Ammonia	H	-	-	-					H	-	-	-
	Bioaerosol	H	V	V	-	Near-linear				H	V	V	-
	NO _x	H	-	-	M					H	-	-	M
	PM	H	-	-	M					H	-	-	M
Observation uncertainty	Odour	V	V	V	-					V	V	V	-
	Ammonia	H	-	-	-					H	-	-	-
	Bioaerosol	V	V	V	-	Near-linear				V	V	V	-
	NO _x	L	-	-	L					L	-	-	L
	PM	M	-	-	M					M	-	-	M
Meteorology	Wind speed	L	L	L	H	H	H	M		M	M	M	M
	Wind direction	L	L	L	H	H	H	M		M	M	M	M
	Temperature	L	L	L	L	L	M	M	L	L	M	M	L
	Cloud cover	M	M	M	M	M	M	M	M	M	M	M	M
	Rainfall	M	M	M	M	L	L	L	L	L	L	L	L
Source definition	Dimensions	M	V	V	M	H	H	H	H	M	H	H	H
	Exit velocity	M	M	H	M	H	L	H	L	H	L	H	L
	Exit temperature	M	V	V	M	H	H	H	L	M	H	H	L
General model performance	Flat terrain	L	L	L	L	H	H	H	H	M	M	M	M
	Buildings	M	M	M	M	H	M	M	M	H	M	M	M
	Complex terrain	M	M	M	M	L	L	L	L	M	M	M	M
	Street canyons	-	-	-	M	-	-	-	H	-	-	-	H
Model limitations	Buildings not modelled with non-point sources					M	M	M	L	M	M	M	L
	Buoyancy and momentum fluxes not modelled for non-point sources			n/a		-	M	M	L	-	M	M	L

- Model limitations

No single dispersion model is able to represent all of the physical and chemical processes that take place during pollutant dispersion. Models neglect processes that in most cases do not influence pollutant

concentrations, but they may also have limitations that are related to programming complexities that have not yet been addressed. For example, local-scale dispersion models such as ADMS and AERMOD may include simple NO_x and SO_x chemistry schemes, but they do not allow for the full chemical processes that lead to the creation of secondary organic and inorganic particles; these processes occur over large temporal and spatial scales over which the local models are not valid, so this is a reasonable model limitation. Bioaerosols are known to coagulate as they disperse downwind; this process would be possible to model given sufficient information, but this complexity is not currently captured by the standard models. Conversely, neither ADMS nor AERMOD are able to model the effect of buildings on the dispersion of emissions from non-point sources; this limitation is related to the complexity of programming, and does restrict model applicability.

Table 9 gives suggested uncertainty ratings related to example model limitations, specifically, buildings not being explicitly taken into account when non-point sources are modelled, and bioaerosols being modelled as passive releases.

2.4 Model features and formulation

The relevant models have been assessed in terms of:

- their ability to model non-point sources, specifically: line, area, volume, jet and road sources;
- the spatial resolutions at which they are applicable i.e. local or regional scale;
- their approach to describing dispersion using meteorological data i.e. Pasquill-Gifford classes or Monin-Obukov length stability classification; and
- their availability in terms of being proprietary, open source or for research use.

Table 10 summarises the models that were reviewed.

The fifth column of this table indicates whether the models were deemed suitable for use in this study. Suitable models are:

- for agricultural and bioaerosol sources: ADMS, AERMOD, AUSPLUME, AUSTAL2000, DISPERSION21, OML, OPS-st, NAME, SAFE AIR, TAPM; and
- for traffic sources: ADMS, AERMOD, CAL3HQC / CAL3HQ, CALINE3 / CALINE4, RLINE.

However, for the reasons summarised in the seventh column of this table, only the following models have been considered further in this report:

- For agricultural and bioaerosol sources: ADMS and AERMOD

Whilst, for agricultural sources in particular, this subset of models appears relatively limited, these are the models that are predominantly used in the UK for modelling agricultural non-point source types. However, ADMS and AERMOD have relatively similar Gaussian plume formulations compared to some of the other models, for example the UK Met Office's NAME model, and the German regulatory AUSTAL2000 model, both of which are Lagrangian models. So, ideally the limitations of ADMS and AERMOD would be assessed alongside these other models; unfortunately the project scope has not allowed this to be done in detail.

Table 10 Summary of models reviewed for application to modelling non-point source emissions *Line, area and volume sources (LAV)

Model	Source Type	Comments	Open source, proprietary or research tool	Suitable for this study?	Used in this study?	Reason for rejection (if applicable)	For suitable models, is deposition modelled?
ADMS	Road, LAV*, jet	CERC model	Proprietary	Yes	Yes		Yes
AERMOD	LAV, horizontal, wind aligned jet sources	USEPA model	Open source	Yes	Yes		Yes
AUSPLUME	-	Australian dispersion model	Open source (required to contact Victoria state government, Australia)	Yes	No	Superseded by AERMOD, not developed beyond Windows XP	Yes
AUSTAL2000	LAV	German Lagrangian dispersion model	Open source	Yes	Yes	Not user friendly; project constraints	Yes
BLP	-	Gaussian dispersion model for buoyant releases from line sources, includes effect of plume rise and downwash. Uses Pasquill-Gifford approach to atmospheric stability.	-	No	No	Obsolete	-

Model	Source Type	Comments	Open source, proprietary or research tool	Suitable for this study?	Used in this study?	Reason for rejection (if applicable)	For suitable models, is deposition modelled?
CAL3HQC / CAL3HQ	Road/Line	A road source model which is a more sophisticated version of CALINE3 for inert pollutants only	Open source	Yes	No	Old model; superseded by CALINE4	No
CALINE3 / CALINE4	Road, Line	Caltrans road source model.	Open source	Yes	No	Project constraints	No
CALPUFF	Area, Line	Gaussian puff model for medium to long range transport	Open source	No	No	Not local scale	-
CTDMPLUS	-	Complex terrain model for point sources; no LAV sources.	Open source	No	No	No LAV sources	-
DISPERSION21	Area, Volume, Street canyons	Swedish Met Office dispersion model.	Open source (required to contact Swedish Met Office)	Yes	No	Difficult to obtain; project constraints.	No
HYPACT	LAV	Lagrangian particle dispersion model. Most suitable when source is small compared to grid size. Local scale & long range transport.	Open source	No	No	AUSTAL2000 would be a preferable model to use; project constraints.	-
ISC3	-	Precursor to AERMOD. Pasquill-Gifford model.	Open source	No	No	Obsolete	-

Model	Source Type	Comments	Open source, proprietary or research tool	Suitable for this study?	Used in this study?	Reason for rejection (if applicable)	For suitable models, is deposition modelled?
LADD	Grid	Multi-trajectory/multi-layer Lagrangian Air-column model	Research model	No	No	Uses Pasquill-Gifford stability categories, unclear source definitions	-
NAME	LAV	UK Met Office Lagrangian model.	Research (available for use under licence)	Yes	No	Project constraints	-
OML (OML-Point and OML-Multi)	Area	Danish Gaussian plume model. OML-Multi is newer version and includes area sources	Proprietary	Yes	No	Project constraints (proprietors offered version for use)	No
OPS-st	Area	Advanced Gaussian "pseudo-linear trajectory" model.	Open source	Yes	No	Project constraints	Yes
OSPM	-	Relevant to street canyons only. ADMS-Roads contains an implementation of this model.	Open source	No	No	Not applicable to all road source types	-
RLINE	Road, Line	Research model for road sources from US EPA	Open source	Yes	No	Project constraints	No

Model	Source Type	Comments	Open source, proprietary or research tool	Suitable for this study?	Used in this study?	Reason for rejection (if applicable)	For suitable models, is deposition modelled?
SAFE AIR	LAV	Gaussian puff model with internal Lagrangian model for dispersion.	Not easily available	Yes	No	Uses Pasquill Gifford stability classes; not easily available	Yes
SCAIL-AGRICULTURE	Area	Screening agricultural tool for ammonia, PM ₁₀ and odour from pig and poultry installations; uses AERMOD.	Open source	No	No	Screening tool; derivative of AERMOD	-
SCREEN3	-	Screening version of ISC3	Open source	No	No	Screening version	-
TAPM	LAV	Australian dispersion model.	Open source	Yes	No	Project constraints	Yes

2.4.1 ADMS and AERMOD model formulation comparison

Section 2.4.1.1 gives details of the different source definitions in ADMS and AERMOD, with Sections A2, A3 and A4 in APPENDIX A giving the corresponding mathematical formulations. The way in which the models account for: dispersion around buildings, plume rise, the temporal variation in emissions, dry deposition, wet deposition and meteorology is discussed in Section 2.4.1.2. Advanced model options are discussed in Section 2.4.1.3.

There are many similarities between the modelling approaches used by ADMS and AERMOD, but there are also differences. The advantages, drawbacks and limitations of the various approaches to modelling non-point sources is discussed in Section 2.4.1.4.

The US EPA's regulatory version of AERMOD is discussed in this section, rather than the commercial implementations of the model.

2.4.1.1 Source descriptions

When considering non-point source types in the different dispersion models, it is important to clarify the underlying source type alongside the way the source is described to the user. For example, in addition to the 'area' source, AERMOD includes an 'area polygon' and an 'area circle' source type. All these sources use the same mathematical expression for the dispersion of the plume, but their source configurations differ.

Table 11 summarises the base non-point source types that are modelled in ADMS and AERMOD. Regarding jet sources, ADMS is able to model a jet that points in any direction, whereas AERMOD is restricted to modelling wind-aligned horizontal point sources.

With the exception of the horizontal point source in AERMOD, the influence of buildings on dispersion is not considered for non-point sources in either ADMS or AERMOD.

Table 12 summarises the non-point source type name that is displayed in the ADMS interface, alongside the source type definition that the model uses internally, and the corresponding base source type as summarised in Table 11. Table 13 summarises the corresponding information for AERMOD.

Table 11 Different non-point base source type *In AERMOD, 'jet' sources are wind aligned horizontal point sources

Base source type	Model	
	ADMS	AERMOD
Area	✓	✓
Volume	✓	✓
Jet / horizontal point source	✓	✓*

Table 12 ADMS source type relationships

Source type name	Source type definition in ADMS input file	Base source type
Line	LINE	AREA
Area	AREA	AREA
Volume	VOLUME	VOLUME
Jet	JET	JET

Table 13 AERMOD source type relationships

Source type name	Source type definition in AERMOD input file	Base source type
Line	LINE	AREA
Area	AREA	AREA
Area Polygon	AREAPOLY	AREA
Area Circle	AREA CIRC	AREA
Volume	VOLUME	VOLUME
Horizontal point source	POINTHOR	POINTHOR

Models have different ways of allowing the user to enter source information. This can be confusing for users, as parameters may be equivalent. For example, volume sources in ADMS have an associated depth, whereas AERMOD volume sources are defined using an initial lateral and vertical spread. These methods are not equivalent. In ADMS the vertical profile is modelled as a sum of error functions representing the material that is initially spread over the specified volume depth. In AERMOD the total plume spread is comprised of the initial spread given by the user and the calculated turbulent plume spread.

Tables 14 and 15 summarise the input parameters for non-point sources in ADMS and AERMOD. In these tables, the source type is as the classification in the ADMS or AERMOD input files i.e. the categorisation given in the second columns of Tables 12 and 13; details regarding the inputs required for the commercial versions of AERMOD have not been discussed as these are non-standard.

Discussing each of these source types in turn:

- Line sources

The geometrical properties of line sources are defined in a similar way in ADMS and AERMOD, with the user specifying the location of two vertices, the line width and a height above ground. In ADMS, users also have the option of entering efflux parameters for the source; these data are not required for AERMOD, which does not model plume rise for non-point sources.

- Area sources

The geometrical information for area sources is entered differently in ADMS and AERMOD. ADMS has a flexible area source type, with 3 – 50 user-defined vertices. AERMOD gives the user three options for defining area sources:

- AREA is used to specify a source corner together with an associated length and optionally with a width and angle from north, if the width is missing the source is assumed to be square and if the angle is missing it is assumed to be zero;
- AREAPOLY is used to specify a polygonal area source of up to 20 vertices, with the coordinates of each vertex given separately;
- AREACIRC is used to specify the centre of a circular source and its radius, but then AERMOD will create a polygonal source of up to 20 vertices to represent the circular area. There is an option for the user to specify the number of vertices used in the representative polygon.

For each of these types the initial vertical plume spread can also be specified.

In ADMS the efflux parameters can be specified for area sources, whereas in AERMOD area sources are always assumed to be passive.

- Volume sources

In ADMS, the dimensions of a volume source are specified by: a set of horizontal vertices; the height above the ground of the source centre; and the initial depth over which the source is well mixed.

In AERMOD a volume source is specified by giving the coordinate of the centre of the source and specifying the initial lateral and vertical plume spread; the volume source is always square.

Although, as discussed above, the different methods used by ADMS and AERMOD to define a volume source are not equivalent, the investigations into generic model behaviour presented in Section 3 indicate that the differences in formulation have little impact on results.

In both models, volume sources are always assumed to be passive and so non-standard efflux parameters cannot be specified.

- Jet / horizontal point sources

In ADMS a jet source is essentially a point source with exit velocity pointing in any direction other than the vertical; this direction is specified by defining the angle from the vertical and a horizontal angle. The coordinates of the point and the diameter is specified and non-zero efflux parameters can also be given.

In AERMOD a directional point source can be specified using the POINTHOR source type, but this is limited to be horizontal and always pointing downstream. As in ADMS, the diameter and efflux parameters can be specified as for a standard point source.

2.4.1.2 *Model features*

It is not only the source definition that differs between ADMS and AERMOD; the models take different approaches to representing:

- dispersion around buildings,
- plume rise,
- the temporal variation in emissions
- dry deposition,
- wet deposition, and
- the boundary layer structure.

Full details of these aspects of the model formulations are given in the associated model documentation. However, a brief summary of the different methodologies has been given below; further details are presented given in tabular format in APPENDIX B.

Regarding meteorology and the boundary layer parameterisation, AERMOD and ADMS are broadly the same as both use Monin-Obukhov similarity theory and an advanced Gaussian model for the plume dispersion, as opposed to Pasquill-Gifford categories. There are some differences between the models; for instance the expressions for the wind speed within the boundary layer are not the same, though the resultant wind speed profiles are virtually identical. The boundary layer height and the heat fluxes obtained are different, though there is no general trend.

ADMS and AERMOD have a broadly similar approach to a modelling the flow and dispersion around a single, wind-aligned building, although the technical details and formulations differ. However, the models have quite different approaches to combining groups of buildings. As this is commonly a necessary step in the process required to create a single wind-aligned building, concentrations predicted by the two buildings modules may differ significantly.

ADMS models plume rise by solving a series of equations for conservation of mass, momentum, enthalpy and emitted material. In contrast, AERMOD uses empirical formulae to calculate the plume rise due to buoyancy and initial momentum.

ADMS and AERMOD have a similar level of flexibility regarding the specification of time-varying factors, for instance hourly, monthly and seasonal values of emission rates, exit temperatures and exit velocities can be specified.

ADMS and AERMOD are both able to model dry deposition of gases by specifying a deposition velocity. ADMS includes an option whereby the deposition velocity is estimated based on the reactivity of the pollutant being modelled. AERMOD users are able to enter a number of physical parameters (for instance, season, land use, diffusivity in air, diffusivity in water etc) which allow the deposition velocity to be estimated. When modelling dry deposition of particles, both ADMS and AERMOD are able to calculate deposition velocities from input particle densities, diameters and mass fractions.

In ADMS and AERMOD, wet deposition can be modelled by calculating the washout coefficient from the precipitation rate. In ADMS, a constant washout coefficient can also be specified; in AERMOD, users are able to enter a number of physical parameters (for instance, scavenging rate, particle diameter etc) which allow the washout coefficient to be estimated.

Table 14 Input parameters required for non-point source types in ADMS

ADMS input file definition	Coordinates			Efflux parameters		Dimensions	Vertices
	X	Y	Height	Exit Velocity	Exit Temperature		
LINE	✓	✓	✓	✓	✓	Width	2
AREA	✓	✓	✓	✓	✓	-	3 – 50
VOLUME	✓	✓	✓	-	-	Depth	3 – 50
JET	✓	✓	✓	✓	✓	Diameter, Jet direction	1

Table 15 Input parameters required for non-point source types in AERMOD; brackets denote parameters that are optional.

AERMOD input file definition	Coordinates			Efflux parameters		Initial Plume		Dimensions	Vertices
	X	Y	Height	Exit Velocity	Exit Temperature	Release Height	Spread		
LINE	✓	✓	(✓)	-	-	✓	(Vertical)	Width	2
AREA	✓	✓	(✓)	-	-	✓	(Vertical)	Length, (Width), (Angle)	1
AREAPOLY	✓	✓	(✓)	-	-	✓	(Vertical)	-	3 – 20
AREACIRC	✓	✓	(✓)	-	-	✓	(Vertical)	Radius	(3 – 20)
VOLUME ^Δ	✓	✓	(✓)	-	-	✓	Lateral, Vertical	-	4 (assumed to be square)
POINTHOR	✓	✓	(✓)	✓	✓	✓	-	Diameter	1

2.4.1.3 Advanced model options

The most commonly used ADMS and AERMOD advanced model options are buildings and complex terrain, but there are many more. All ADMS and AERMOD advanced model options are summarised in Table 16. The compatibility of the advanced model options with each of point, area, volume and jet source types, for both ADMS and AERMOD is given. Where there are restrictions regarding model behaviour, clarification is given in the 'Comments' column.

Table 16 Compatibility of advanced model options with point (P), Area (A), Volume (V) and Jet (J) sources

	ADMS				AERMOD			
	Point	Area, Volume	Jet	Comments	Point	Area, Volume	Jet	Comments
Deposition	✓	(✓)	(✓)	Falling drop wet deposition not compatible with A, V, J	✓	✓	✓	
Radioactive decay	✓	✓	✗		✗	✗	✗	
Gamma dose	✓	✗	✗		✗	✗	✗	
Odours	✓	(✓)	✓	Odour cannot be modelled with V	✗	✗	✗	
Plume visibility	✓	✗	✗		✗	✗	✗	
Chemistry	✓	✓	✓		✓	✓	✗	
Complex terrain	✓	✓	✗		✓	✓	✗	
Buildings	✓	(✓)	(✓)	A, V, J are modelled but do not include building effects	✓	(✓)	✓	A, V are modelled but do not include building effects
Coastline	✓	✗	✗		✗	✗	✗	
Puff	✓	✗	✓		✗	✗	✗	
Fluctuations	✓	✓	✗		✗	✗	✗	
Marine boundary layer	✓	✓	✓		✗	✗	✗	
Temperature and humidity output	✓	✗	✗		✗	✗	✗	
User-entered 3D flow field	✓	✓	✗		✗	✗	✗	
Calm conditions	✓	✓	✗		✗	✗	✗	
Time-varying sources	✓	✓	✓		✗	✗	✗	
Wind turbine effects	✓	✓	✗		✗	✗	✗	

2.4.1.4 Drawbacks and limitations

Neither ADMS nor AERMOD allow for the dispersion around buildings when modelling non-point sources. This is a limitation with regard to the modelling of agricultural and bioaerosol sources because these are usually less well-defined releases that are better represented by area and volume sources. One common approach to allow for the influence of buildings is to replace the non-point sources with a series of point sources with emission characteristics that are representative of the non-point source in question. This approach works well when the release is passive or only slightly buoyant with low initial momentum. For moderately or highly buoyant releases with significant initial momentum, however, the plume rise and associated entrainment of a point source release differs significantly from that from an area or volume source, so the approximation does not work well.

Another way to represent the impact of buildings on the release is to increase the surface roughness parameter, z_0 , in the vicinity of the buildings. In AERMOD, this can be done by using roughness lengths that vary by wind sector, with the wind sectors defined according to the location of the building relative to the source. A similar approach can be taken in ADMS by using different values of z_0 for each hour. Alternatively, in ADMS, the user is able to specify the spatial variation of surface roughness.

Neither ADMS nor AERMOD models plume rise for volume sources. This is because volume sources are used to represent diffuse sources for which efflux conditions are assumed to be unimportant. However, there may be cases where a volume source is appropriate because of the spatial distribution of a number of small sources, but the initial buoyancy and momentum fluxes *are* important. Further, in AERMOD version 14134, plume rise cannot be modelled for line and area sources; this is likely to be a restriction for modelling a number of sources where efflux parameters influence dispersion.

There are a number of agricultural and bioaerosol emission sources that could be more precisely defined than an 'area' or 'volume' source. For example, baffles are often used as an abatement measure to reduce the particulate concentrations emitted via fans on poultry housing. The presence of baffles alters the flow from the fans, rather than jet-like emissions from the vertically mounted fans, emissions generally occur from an open horizontal gap usually at a few metres above the ground level. Under minimum and low transitional ventilation rates the efflux velocity is generally low (<1 m/s) and, apart from in very light winds, the plume is likely to be rather incoherent. A more significant emission velocity and more coherent plume is likely at greater ventilation rates, although high ventilation rates only occur in warmer weather when the crop is in the latter stages.

Similarly, the source characteristics of windrows differ when they are subject to turning compared to when they are not. Some automation by the model of the increase in temperature and initial momentum of the release, and the change to the physical dimensions of the source relating to this activity, may improve the model results.

2.5 Parameter space for idealised modelling

The literature review described in Sections 2.2.1 to 2.2.3 informs the model input 'parameter space' for the idealised modelling i.e. the set of all possible combinations of values for all the different input parameters; traffic modelling has not been included in the idealised modelling due to project constraints. For each of agricultural sources and bioaerosol and biowaste / composting facilities separately, appropriate non-point source types have been selected to represent the sources, based on those used in the literature. For each source type, a range of model input parameters have been chosen, again related to those values used in the literature.

Table 17 summarises the parameter ranges for agricultural sources. Whilst the source heights, depths and efflux parameters relate to the majority of sources in the real world, the horizontal dimensions of the source (length and width) usually relate to the building dimensions. For the idealised modelling, 'typical' building dimensions of 60 m x 10 m have been assumed; these dimensions do not alter the general behaviour of the models.

Particular features of the sheds lend themselves to being modelled using different source types. The level of refinement used to represent a particular source should relate to the source to receptor distance; if this is relatively large, there is little advantage in modelling all source characteristics in detail. However, it is important to correctly account for buoyancy and initial plume momentum when these are significant, and also the presence of buildings, where feasible, as these aspects of the source characterisation may impact on the concentrations up to a few kilometres downwind of the source. Possible methodologies for detailed modelling of tunnel ventilation (vertically mounted fans and baffles), side fans, capped ridge fans, natural ventilation and free-range areas are given below; these methodologies are those suggested by the authors and other representations may also be suitable.

- **Tunnel Ventilation**

1. Traditionally *vertically mounted fans* in the gable end of the house at 1 to 4 m above ground level. These are often modelled using a volume source, for example with dimensions that encompass the shed width and extending some distance out from the shed to approximately represent the initial entrainment with the ambient air; total source depths are usually ~1 m. However, as volume sources in ADMS and AERMOD do not allow for plume rise, it may be that a volume source representation leads to an over-prediction of ground level concentrations i.e. modelled concentrations would be conservative. For detailed modelling, it may be more appropriate to use a source type that allows for plume rise, for example a jet which

is able to account for the directional nature, initial momentum and buoyancy of the jet⁵.

Note that if deposition is being modelled, volume sources should not be configured with a base at ground level, as this will lead to an over prediction of deposition near the source.

2. A *baffle* can be fitted to the gable end of a shed in order to deflect the plume from the fans with the intention of allowing some settling of dust; water traps are sometimes included in this arrangement to increase the efficiency of this abatement technology. The baffle reduces the efflux velocity to a relatively low value, so volume sources can be used, with dimensions corresponding to the width of the shed, extending a short distance out from the shed (for instance, 2 m) and 2 – 3 m above the height of the exit point of the baffle.

However, as ADMS and AERMOD volume sources do not allow for plume rise, high ventilation rates during the summer and relatively warm releases during winter may lead to significant vertical efflux velocities and exit temperatures which should be accounted for; if plume rise is neglected, the predicted modelled concentrations will be a conservative estimate. Whilst it is not common practice to use an area or line source in this situation, these source types would be more appropriate and a dispersion model that allows for buoyancy and the initial momentum of releases should be used in this case.

3. Increasingly, tunnel ventilation is being provided by a bank of *horizontally mounted high velocity fans* in a tower at the end of the house; such an arrangement should be modelled using point sources.

- **Side Fans**

If side fans have moderate to high buoyancy and/or initial momentum, and these efflux parameters are known, it is recommended that a jet or line source is used to represent each bank of fans; modelling in this way should give reasonable model predictions in the near and far field.

For low ventilation rates, or where efflux parameters are unknown, a single volume source may be used, extending from ground level to approximately gable height. Where emission rates vary across a site, each building should be treated as a separate volume source. The volume source representation in ADMS and AERMOD is likely to result in conservative prediction of modelled concentrations due to plume rise being neglected.

⁵ Note that jet sources in AERMOD are horizontal and wind aligned so may not be appropriate in all cases.

- **Capped ridge fans**

These are subject to large downwash effects and therefore should be modelled using large diameter low efflux velocity point sources with buildings, or a volume source. If using a volume source then the base should be somewhat lower than the actual source height to allow for downwash effects.

- **Natural ventilation**

There are many source configurations that can be used to represent natural ventilation. Volume sources are recommended and should be arranged so as to mimic the emission characteristics. Generally the base height should be lower than the actual emission point to account for building effects; as a rule of thumb for side vents, the volume source should be placed at ground level, with a depth approximately two-thirds of the building height.

Ridge vents are sometimes employed, with the intention of the design being that buoyancy effects draw air in through side vents which then exits through the ridge vent. However, in reality, in moderate to high wind conditions, dynamic wind pressure causes cross flow in the house which disrupts such effects and there are usually significant fugitive emissions from the inlet vents. In this case, a proportion of the emissions should be from a low level volume source representing fugitive emissions from the inlet vents and a proportion from a higher level volume source (or a series of large diameter low efflux velocity point sources) representing the ridge vent. The proportions can be varied depending on wind speed.

The geometry of inlet vents is often altered using shutters (for instance, the Galebreaker System in some pig housing, or manually operated canvas shutters in duck and turkey houses); where critical, such alterations to the source characteristics can be represented using separate volume sources and changing emissions appropriately. For example, the 'Galebreaker' sides will be mostly closed in cooler and windier weather, so most emissions occur from the gap between the top of the shutters and the gable; conversely in hot weather and when there are light winds, the sides will be fully open and emissions may occur from a lower point on the building, depending on wind speed or temperature.

- **Ranging/grazing area and open lots/yards**

Area sources are generally used to model free-range areas, although a shallow volume source would also be appropriate.

Table 18 summarises the parameter ranges for windrow sources; other bioaerosol sources have not been considered explicitly due to a lack of information regarding the range of source parameters available in the literature. As for agricultural sources, whilst the source heights, depths and efflux

parameters relate to the majority of sources in the real world, the horizontal dimensions of the source (length and width) relate to the windrow dimensions. For the idealised modelling, 'typical' windrow dimensions of 80 m x 20 m have been assumed; these dimensions do not alter the general behaviour of the models.

Particular features of bioaerosol sources lend themselves to being modelled using different source types. As for agricultural sources, the level of refinement used to represent a particular source should relate to the source to receptor distance and buoyancy and initial momentum should be accounted for when appropriate. Possible methodologies for detailed modelling of composting windrows, manure heaps, biofilters, slurry/waste water lagoons and tanks are given below; these methodologies are those suggested by the authors and other representations may also be suitable.

In most cases, emissions from bioaerosol sources are highly uncertain. Consequently, although appropriate source dimensions should be specified in a modelling exercise, detailed refinement of source characteristics may be inappropriate. Instead, results from sensitivity analyses where a range of emission rates have been applied to a relatively simple model configuration may give a reasonable indication of the likely impact of bioaerosol source types.

- **Composting windrows and manure heaps**

In most cases, the air close to the surface of manure and compost heaps exceeds the ambient temperature, with the temperature increment being related to the amount of activity within the windrow. The warmth of the biodegrading material leads to some plume rise, which will be most noticeable in light winds. An appropriate source type that allows for plume rise should ideally be used, for example an area source modelled at above ambient temperature with a low efflux velocity.

If windrows or heaps are disturbed, by shredding processes, turning, loading, or spreading, hot material from inside the windrow / heap is exposed and the pollutant release may be subject to significant plume rise, which is likely to be inhomogeneous and chaotic over the source, rather than the release rising as a coherent structure. During shredding and turning, pollutant levels are very high whilst the disturbance occurs; they tend to decay exponentially back to stable levels within a few days.

From a pragmatic point of view however, for the majority of time, plume rise is minimal for these sources, and the release properties such as temperature are usually unknown; emissions are also highly uncertain. Consequently, volume sources are often used rather than area sources, with the depth representative of the windrow height, for instance 2-5 m.

Deposition (and consequently plume depletion) of bioaerosols is likely to be significant for particles greater than approximately 10 μm in diameter in the mid to far field. Improved understanding of the coagulation processes that occur in the vicinity of composting sites would inform the

choice of particle size distribution and deposition parameters used in dispersion modelling.

- **Biofilters**

Emissions from the surface of bio-filters may occur at ground level or from several metres above the surface. In either case, an area source may be used to represent the emissions, as the volumetric flow rate through the bio-filter and surface area are usually known and can be used to calculate an efflux velocity (usually ~ 0.1 m/s).

Elevated emission surfaces may be subject to considerable downwash effects; to allow for this, the modelled height should be slightly lower than the actual height, or the emission can be modelled as an array of point sources which allow for downwash. The temperature of bio-filter releases is usually a few degrees higher than ambient conditions and, for the majority of applications, there is a minimum exit temperature independent of ambient temperature.

A bio-filter may be served by one or more stacks, in which case a point source should be used.

It is worth noting that bio-filter performance usually fluctuates and periodically abatement technologies may fail. Consequently, modelling a continuously high abatement efficiency scenario is likely to lead to an under prediction in modelled concentrations; zero abatement can be assumed as a worst case scenario.

- **Slurry / waste-water lagoons and tanks**

The surface of a slurry lagoon may be below ground level, or above ground level surrounded by banking. In the case of the former, an area source at ground level should be used, with the emission rate calculated from surface area of the lagoon; where appropriate, the source dimensions should relate to the hole in which the lagoon lies. Emissions are usually passive.

Above ground lagoons and tanks may be treated similarly, but in order to account for downwash, the height of the modelled source may be set lower than the height of banking or the height of the tank. In the case of an above ground lagoon, the initial vertical dimension of the source may be less well defined; therefore, a shallow volume source would better represent the emission characteristics, again with some adjustment of base height to account for possible downwash effects.

Table 17 Agricultural source parameter ranges

Example real-world sources	Idealised source type	Source dimensions (m)				Efflux parameters		Literature references
		Height	Length	Width	Depth	Temperature (°C)	Velocity (m/s)	
Sheds with tunnel ventilation with long line of gable-end fans; wide sheds; naturally-ventilated shed with side inlets and roof exit; side vents which direct the air flow to ground level	Line	0 – 2	60	1	n/a	Ambient; ambient + 5; ambient + 10	0	UK Environment Agency AQMAU, 2010, Hill et al, 2014
Slurry lagoon, slurry tank, pig houses.	Area	0 – 2	60	10	n/a	Ambient, Ambient + 5, Ambient + 10	0, 0.1	Theobald et al, 2010, Schulte <i>et al.</i> , 2007, Hill et al, 2014
Sheds with tunnel ventilation with long line of gable-end fans; wide sheds; naturally-ventilated sheds; side vents which direct the air flow to ground level; pig houses.	Volume	1.25 – 2.5	60	10	2.5 – 5.0	Ambient, Ambient + 5, Ambient + 10	0	UK Environment Agency AQMAU, 2010, Hill et al, 2014, Theobald et al, 2010, Schulte <i>et al.</i> , 2007
Sheds with tunnel ventilation with long line of gable-end fans; wide sheds	Jet	1 – 5	-	-	-	Ambient, Ambient + 5, Ambient + 10	0.5, 7.5, 15	UK Environment Agency AQMAU, 2010, Hill <i>et al.</i> , 2014

Table 18 Bioaerosol source parameter ranges

Example real-world sources	Idealised source type	Source dimensions (m)				Efflux parameters		Literature references
		Height	Length	Width	Depth	Temperature (°C)	Velocity (m/s)	
Open windrow, vertical flow composting technology.	Area	0 - 5	80	20	n/a	15, 25, 35	0 – 0.3, 2.95	ADAS/SWICEB, 2005, Drew <i>et al.</i> , 2006, CERC, 2009, Swan <i>et al.</i> , 2003, Douglas, 2013
Open windrow	Volume	1.25 – 2.5	80	20	2.5, 5.0	15, 25, 35	0	ADAS/SWICEB, 2005, Drew <i>et al.</i> , 2006, CERC, 2009, Swan <i>et al.</i> , 2003,

2.6 Case studies

The literature review highlighted many datasets that had the potential for use in this project. However, the authors found the majority of these datasets were not available for use. The main reason for this appeared to be that the groups that held the data did not have sufficient resources to compile the data into a format that could be passed on to a third party. There were also issues with ownership of certain datasets. The consequence of this was that the authors spent a significant amount of time trying to obtain datasets for use, to no avail. Further, once the datasets had been obtained, there was in some cases missing information that would have been useful for the modelling; although some effort was made to obtain additional data, in these cases it was necessary to make assumptions in the modelling.

The datasets that were collated for use in this project were:

- The Sniffer Whitelees and Glendevon datasets

The authors gratefully acknowledge those who funded the original ER26 SCAIL Agriculture project, specifically the Scottish Environment Protection Agency, the Northern Ireland Environment Agency, the Environment Agency and Environmental Protection Agency (Republic of Ireland), and also Alan McDonald (SEPA), Rob Kinnersley (Environment Agency) and Michelagh O'Neill (Sniffer) for helping to make this dataset available for use.

- The poultry dataset reported by Demmers (2009) and Demmers *et al.* (2010).

The authors gratefully acknowledge Defra for funding this work (project AC104) and Theo Demmers (Royal Veterinary College) who supplied the dataset and spent time with the authors answering questions.

- The bioaerosol datasets reported in Williams *et al.* (2010)

The authors gratefully acknowledge Defra for funding this work and Sean Tyrell, Gill Drew (both at Cranfield University) and Philippa Douglas (Imperial College) who supplied the dataset and spent time with the authors answering questions.

These datasets are described in the following sections.

The Sniffer studies were set up in order to validate the performance of AERMOD within the SCAIL Agriculture Tool. These datasets are therefore directly suitable for evaluation of dispersion models in this project. Conversely, the Defra poultry and bioaerosol studies were designed for other purposes, for example, to assess abatement techniques and to find out whether odour is an appropriate measure of bioaerosol concentration. As a result, the statistical analyses performed for Whitelees are more informative regarding dispersion model performance than the results from the other studies.

2.6.1 Sniffer Whitelees and Glendevon datasets

2.6.1.1 Study description

The Whitelees farm had emissions from 37 000 layers in eight poultry sheds. The study included onsite meteorological measurements including wind speed, wind direction, precipitation, surface moisture, relative humidity and air temperature. The meteorological data were recorded at 30 minute intervals.

The Whitelees study included one continuous monitoring site where measurements of total particles, PM₁₀, PM_{2.5}, PM₁, and ammonia were taken at 15-minute intervals. Additionally, some hand-held PM₁₀ measurements were made across the site; ammonia measurements were made at nine locations around the farm, with a sample height of 1.5 m; some field odour measurements were also taken. Vent PM₁₀, odour and NH₃ measurements were recorded in order to derive emission estimates.

Glendevon farm has emissions from 45 000 birds in five poultry sheds. As at Whitelees, onsite meteorological measurements were made. Hand-held PM₁₀ measurements were made across the site; ammonia and odour observations were also recorded, but no continuous monitoring was performed.

2.6.1.2 Dataset selection

Whitelees was selected as the superior dataset as there was continuous monitoring during this campaign. After modelling Whitelees, the authors decided that there was not sufficient justification for additionally modelling Glendevon, as the non-continuous measurements taken during these studies were less conclusive in relation to the project aim i.e. the evaluation of the strengths and weaknesses of modelling using the different non-point source types.

Unfortunately, the continuous PM₁₀ measurements at Whitelees were not considered sufficiently robust for use in modelling. There were a number of reasons for this, including: during the first eight days of the campaign, data capture was poor due to power outages; when the continuous monitoring data were compared to measurements using other samplers, the comparisons were poor; and the report states that 'clearly some other significant [PM] sources are present'.

2.6.2 Defra poultry datasets

2.6.2.1 Study description

This study involved taking PM₁₀ and PM_{2.5} measurements at eight farms. The farms included those breeding broilers, caged egg layers and free range animals and the project assessed the effectiveness of emission abatement systems, specifically the use of baffles and filtration. Measurement campaigns were undertaken during the summer and winter at most of the farms during both 'light' and 'dark' periods, which corresponded to when the lights were on and off in the sheds, rather than to day and night. Although data for all farms were provided to the authors, project resources did not allow all farms to be modelled; specifically, two of the broiler farms were selected for modelling following advice from Theo Demmers that these were the most robust datasets.

These datasets have been anonymized in order to protect the privacy of the farm owners. Measurements were taken at some, but not all of the following locations:

- 50 m upwind of the source;
- at the source; and
- downwind of the source, between 50 and 400 m.

Unfortunately, the authors were not able to obtain the exact times and locations of these downwind measurements^{**}. That is, measurements have been supplied for each of the 'light' and 'dark' periods separately, but the time and duration of the measurements is unknown.

2.6.2.2 *Dataset selection*

Farm F is an arable farm that houses approximately 180 000 broilers in six sheds. The monitoring equipment was deployed in the vicinity of three of the sheds that house approximately two thirds of the birds. These sheds all have three fans, which are each located on one of the end walls and draw air through the shed. The air enters the shed through the side walls; this ventilation system is described as an 'End Ventilation System'. The remaining birds are housed in the three other sheds; two of these have capped ridge mounted fans and the other has uncapped high speed ridge mounted fans, each with a short chimney.

Farm G uses an 'End Ventilation System' on six sheds in a farm that houses nearly 200 000 birds. This farm also includes an emissions abatement system where the air leaving the sheds passes through a baffle. The baffle was designed to hold water, but the campaign documentation states that water was not present in the chamber due to leakage; it is not clear whether this is the case for all baffles from the six sheds, or just the shed where the fan exit concentrations were measured. All fans are likely to be in the same place on each shed, and with similar specifications.

Although data were collected on two visits to these farms (summer and winter) only the winter cases have been modelled. This is because the wind conditions in the summer cases were light and variable, which makes the concentration measurements unreliable in terms of representing downwind dispersion of the emissions from the shed. Even in the winter case, for some of the periods, the upwind measurement exceeded the downwind measurements and/or the downwind measurements increased rather than decreased with distance from the shed. These 'inconsistencies' in the measurements may be due to observational error in terms of the monitoring equipment not capturing the

^{**} The measurements taken during this campaign were made by HSL and CEH. Despite correspondence with HSL and attempts to contact CEH, data, including the times associated with the measurements, has not been forthcoming.

plume; alternatively the complexity of the near-source flow fields may lead to non-monotonically decreasing concentration values.

2.6.3 Defra composting datasets

2.6.3.1 Study descriptions

This study involved taking measurements of various bioaerosols at four composting facilities using a variety of measurement techniques. Measurement campaigns were undertaken seasonally. Although data for all four facilities were provided to the authors, project resources did not allow all sites to be modelled; specifically, one of the facilities was selected for modelling following advice from collaborators at Cranfield. These datasets have been anonymized in order to protect the privacy of the facility owners. Measurements were taken nominally at an upwind location, at the source, and at three or four downwind distances. The exact location of the measurements varied according to the practicalities on site, so the 'source' measurement was often just as close as possible to the source. The measurements are sensitive to the technique used – some devices perform better when concentrations are high and vice versa. The emission rate of the source was not measured, but has to be estimated from the measured concentrations. Emission rates are very hard to ascertain and can vary by orders of magnitude depending on the site activity. The data also includes meteorological observations made at the same time as the concentration observations, with the majority of wind direction measurements accurate to the nearest 22.5°.

2.6.3.2 Dataset selection

Cranfield advised that Site B was the best dataset to use as it was the smallest, least-complex site where only one source activity occurred at any particular time. There was only one building (a 'Portakabin' office). It is not known which site activities were ongoing during the measurement campaign. Anonymised aerial photography was provided for the site but windrow locations change regularly; the aerial imagery is anonymised with no scale. There is therefore uncertainty regarding the source size location for this dataset.

Monitor locations are categorised according to the distance from the source. Three types of samplers were used: IOM, CEN, Andersen. Each sampler has different issues and effectiveness. For example, close to the source the Andersen sampler is quickly overloaded and the IOM is not effective at low concentrations. Cranfield advised that the IOM measurements are best to use in the first instance.

The majority of samplers run for 30 minutes and bacteria accumulate on an agar plate, although the Andersen sampler runs for 10 minutes. The measured concentration of colony forming units per unit area is the total accumulated during this sampling period. However, there are some complex issues, including that some of the bacteria may die during the sampling period. For the IOM filter there is a detection threshold of 278 cfu/m³ for a 30 minute sample period and 185 cfu/m³ for a 45 minute sample period. In the dataset provided by Cranfield, these detection limits are used to indicate any measurements within the ranges 0 to 278 cfu/m³ (30 minute sample) and 0 to 185 (45 minute sample).

Different types of bioaerosol have been measured: *Aspergillus fumigatus*; total bacteria, gram-negative bacteria; glucans; endotoxins. Some particulates were also measured. After examining the data provided, the total bacteria measurements were chosen for use in this study as these appeared to be the most robust dataset; the authors were advised to ignore measurements of *Coriaria* spores, glucans and endotoxins due to complex issues with recording those bioaerosol concentrations.

3 TASK 2: GENERIC MODEL BEHAVIOUR

3.1 Overview

A modelling exercise has been performed using ADMS and AERMOD. For each model, predicted downwind concentrations for different source types and input parameters are compared. The sources modelled have parameters that are representative of agricultural sources (primarily emissions from intensively farmed rather than free-range animals) and bioaerosol sources (primarily emissions from windrows).

Two sets of idealised modelling scenarios have been run: single meteorological conditions (Section 3.2) and annual runs (Section 3.3). The parameter ranges used for this set of runs have been derived from the parameters found in the literature, as summarised in Tables 17 and 18. Due to the large number of results presented, the majority of the figures relating to this task are given in APPENDIX B.

The emission rate for the idealised agricultural source was taken to be representative of ammonia emissions and the emission rate for bioaerosols is representative of Colony Forming Units (CFUs) from a biowaste facility; details are given in Table 19. The surface roughness length for all cases was taken to be 0.2 m, which is representative of agricultural areas in the UK.

Table 19 Typical emission rates

Idealised source type	Emission rate	Comment
Agricultural	0.0475 g/s	Equivalent to 1500 kg/yr
Bioaerosol	3.0×10^7 cfu/s	Units are 'colony forming units'. Equivalent to 50000 cfu/m ² /s for typical open windrow dimensions. This is roughly a median between low emission rates (no activity) and large emission rates (high activity, e.g. shredding or turning).

3.2 Individual meteorological conditions

For the individual meteorological conditions, example conditions have been used which correspond to stabilities varying from the most stable to highly convective. These are presented in Table 20.

The full parameter space of model inputs in terms of:

- meteorological conditions,
- source dimensions (height, length, width, depth, orientation), and
- efflux parameters (temperature and velocity)

is large, so a subset of results has been selected for inclusion in this report. Specific details of the parameter values selected are given in Table 21 for agricultural sources and Table 22 for bioaerosol sources. Concentrations were modelled up to 10 km from the source, but as concentrations decay rapidly near the source, only near-field results have been presented in the plots.

For reference, the source orientation with respect to the wind is shown in Figure 2. Figure 3 presents the source configurations for each source type, for the 90° orientation. The modelled receptors, which are at 1 m intervals up to 10 m from the midpoint of the source, 2 m intervals between 10 and 100 m, 10 m intervals between 100 m and 1 km and 100 m intervals between 1 km and 10 km, are shown. The line source horizontal dimensions are 10 m by 1 m; the area and volume source dimensions are 60 m by 10 m and the jet source has a diameter of 1.2 m.

Table 20 Meteorological data

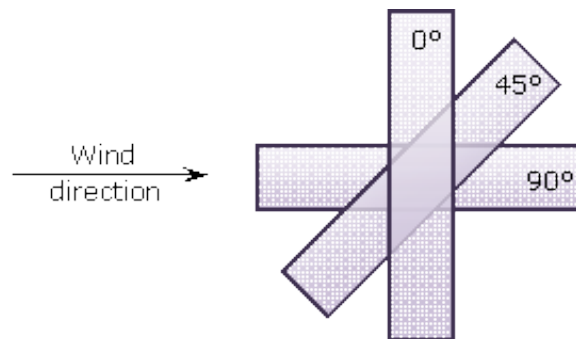
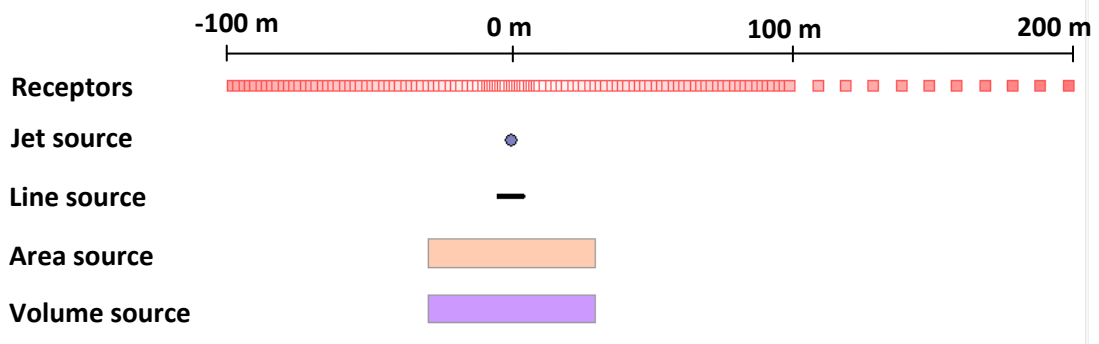
Met condition	Temp (°C)	Wind speed (m/s)	Wind direction (°)	Cloud cover (oktas)	Surface sensible heat flux (W/m ²)	u* and w* [calculated] (m/s)	H/L _{MO} [calculated]
Convective (B)	16.3	1.5	270	6	75.5	0.206, 0.817	-24.8
Neutral (D)	14	4.1	270	8	0	0.417, 0	0
Stable (F)	6.3	2.1	270	8	-9.2	0.165, 0	2.04

Table 21 Agricultural source parameter ranges for single meteorological condition idealised modelling runs; values in bold indicate the default conditions

Idealised source type	Source dimensions (m)			Efflux parameters		Met conditions (Table 20)
	Height	Orientation (°)	Depth	Temperature (°C)	Velocity (m/s)	
Line	0	0	n/a	Ambient	0	B
	2	45		Ambient + 5	0.1	D
		90		Ambient + 10		F
Area	0	0	n/a	Ambient	0	B
	2	45		Ambient + 5	0.1	D
		90		Ambient + 10		F
Volume		0	3.75	Ambient		B
	1.875	45		Ambient + 5	0	D
		90		Ambient + 10		F
Jet	1	Wind-aligned	n/a	Ambient	0.5	B
	3			Ambient + 5	7.5	D
	5			Ambient + 10	15	F

Table 22 Bioaerosol source parameter ranges for single meteorological condition idealised modelling runs; values in bold indicate the default conditions

Idealised source type	Source dimensions (m)			Efflux parameters		Met conditions (Table 20)
	Height	Orientation (°)	Depth	Temperature (°C)	Velocity (m/s)	
Area	0.0	0	n/a	15	0.00	B
	2.5	45		25	0.30	D
	5.0	90		35	2.95	F
Volume	1.875	0	3.75	15	0	B
		45		25		D
		90		35		F

**Figure 2 Definition of source orientation with respect to the wind direction for the single meteorological condition runs****Figure 3 Source representations for idealised sources**

3.2.1 Results summary

The results of the individual meteorological cases have been presented in Figures 45 to 48 for the agricultural sources and Figures 51 and 52 for the bioaerosol sources. The ADMS and AERMOD results have been presented alongside each other but they have not been compared directly or discussed on a case-by-case basis in terms of magnitude, location of maximum concentrations etc due to the quantity of cases considered. The annual modelling runs presented in Section 3.3 show typical, overall differences in concentrations predicted by the models, when real-world combinations of meteorological parameters and orientations are taken into account.

3.2.2 Discussion

In the following discussion, the response of each source type to the variation of input parameters has been considered in turn. For area and volume sources, the idealised agricultural and bioaerosol source types are discussed separately.

Overall, in the near field (<100 m), the concentrations from the line sources are at least an order of magnitude higher than from the area sources because the along-wind and cross-wind source dimension is smaller compared to the area and volume sources (refer to source configurations given in Figure 3). This highlights the necessity of modelling sources at sufficiently high detail if near field concentrations are important.

3.2.2.1 Line sources

Figure 45 presents the comparison of line source results from ADMS and AERMOD.

Concentrations predicted in the vicinity of the source (< 20 m) are very sensitive to source height (Figure 45 d)). For ADMS, further downwind the solutions associated with the two source heights quickly converge; for AERMOD, they are approximately the same (Figure 4).

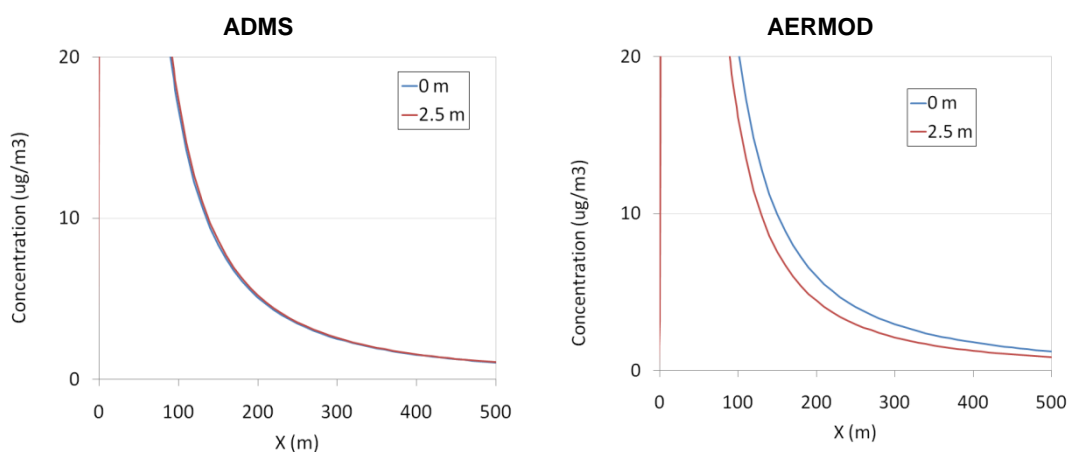


Figure 4 Far field behaviour of ADMS (left) and AERMOD (right) for agricultural line sources with varying source height; note that for ADMS, the two lines are approximately overlaid for distances of > 100 m.

Neither ADMS nor AERMOD show any variation of concentrations with efflux conditions (exit temperature and velocity, Figure 45 a) and b)) for neutral meteorological conditions. For ADMS, this is because the buoyancy and initial momentum of the release were not sufficient for the lift off condition to be satisfied for this ground-level source i.e. no plume rise was modelled. In AERMOD, line sources are always passive releases, so predicted concentrations are independent of efflux conditions.

In terms of results when the orientation of the source is changed, the near-source behaviour differs, but in the far field, both ADMS and AERMOD results are independent of source alignment (Figure 45 e)). ADMS predicts approximately the same peak concentration within the source, for all source alignments, but

AERMOD predicts a higher concentration for the wind-aligned source. The concentration is determined by a combination of the source component upwind of the receptor point and lateral spread. For a long thin line source (i.e. aligned with the wind) the source contribution is large, but the lateral spread reduces concentrations significantly. Conversely for a wide narrow line source (i.e. perpendicular to the wind) there is a relatively small source contribution but lateral spread is relatively reduced. In ADMS these effects approximately cancel; in AERMOD the source orientation dominates.

For both ADMS and AERMOD, maximum concentrations occur for stable conditions (Figure 45 c)). However, for ADMS, minimum concentrations occur for neutral conditions, but for AERMOD, minimum conditions occur for the convective case. The difference in behaviour is related to the different meteorological pre-processors used by the model. In ADMS, for this particular case, the meteorological pre-processor predicts that the friction velocity for neutral conditions is higher than for convective conditions, which leads to increased plume spread for the neutral case; for a ground level source, higher plume spread leads to lower ground-level concentrations.

In terms of magnitudes of concentrations, AERMOD generally predicts higher concentrations than ADMS for the cases considered.

3.2.2.2 *Area sources*

Figures 46 and 51 present the comparison of area source results from ADMS and AERMOD for agricultural and bioaerosol sources respectively.

Agricultural sources

As for line sources, ADMS predicts that the buoyancy and initial momentum of the release is insignificant for neutral conditions because the release does not have sufficient buoyancy or momentum for lift-off, whilst in AERMOD, area sources are always treated as passive. The concentrations predicted in the vicinity of the source (< 100 m) are very sensitive to source height. For ADMS, further downwind the solutions associated with the two source heights quickly converge; for AERMOD, they are approximately the same.

Both models follow the same pattern of behaviour when considering the variation of source alignment; for AERMOD this is similar to the line source behaviour, for ADMS, a decreased peak concentration is now seen when the source is not aligned with the wind.

ADMS predicts that lift off occurs for the low-wind speed stable and convective meteorological conditions, leading to relatively low ground-level modelled concentrations for these cases. In terms of magnitudes of concentrations, when the lift-off condition is not satisfied in ADMS, the near-source concentrations are very similar in ADMS and AERMOD; predicted concentrations may differ by orders of magnitude, however, in certain meteorological conditions, for example the stable case.

Bioaerosol sources

The efflux conditions for bioaerosol sources are much higher than for agricultural sources; as a result, plume rise is modelled in ADMS for all cases considered. The ADMS results vary with exit temperature and exit velocity as expected i.e. increased efflux leads to reduced ground-level concentrations. AERMOD models area sources as passive releases, so ground-level concentrations are independent of variations in plume rise and exit velocity.

For both ADMS and AERMOD models, increasing the source height decreases ground level concentrations, as would be expected; model behaviour for agricultural and bioaerosol area sources are the same with respect to changing the orientation of the source.

For ADMS, the predicted ground-level concentrations are lowest in stable conditions, and highest in neutral conditions; for the stable case, the low ground-level concentrations are a result of plume buoyancy (the release is 25°C and the ambient temperature is 6.3°C) and for the neutral case, the high wind speed inhibits plume rise resulting in relatively high ground-level concentrations. Conversely, AERMOD has its highest concentrations for stable wind conditions due to plume rise not being modelled; the ordering of the convective and neutral cases is related to the balance between the mechanical turbulence generated by the wind speed and the convective turbulence relating to the ambient conditions.

In ADMS, bioaerosol sources are usually modelled as buoyant releases with low initial momentum. For some meteorological conditions, the plume rise modelled in ADMS leads to predictions of ground-level concentrations an order of magnitude lower than those predicted by AERMOD, because AERMOD neglects plume rise for area sources.

3.2.2.3 Volume sources

Figures 47 and 52 present the comparison of volume source results from ADMS and AERMOD for agricultural and bioaerosol sources respectively.

Agricultural sources

The volume source considered in these test cases has horizontal dimensions of 10 m by 60 m. AERMOD is only able to model volume sources that have square horizontal dimensions. Consequently, the idealised source in AERMOD is a combination of six volume sources. This means that within the source itself, predicted concentrations are not monotonically increasing i.e. the concentration profiles are 'spiky'. If sufficiently small volume sources were considered, the size of these spikes could be reduced.

As for line and area sources, there is no variation in results with efflux parameters; for both ADMS and AERMOD this is because the release is treated as passive. The volume source results in terms of varying the source orientation follow the same pattern as for area sources.

In terms of meteorology, the ordering of maximum concentrations for both models is consistent with the line source results i.e. the magnitude of the plume

spread driving dispersion near the ground is related to the friction velocity, which differs between ADMS and AERMOD.

The magnitude of concentrations predicted by ADMS and AERMOD is similar for the neutral stability condition considered, but differs when meteorological conditions are varied.

Bioaerosol sources

As neither ADMS nor AERMOD model plume rise for volume sources, model results for the agricultural and bioaerosol idealised runs are identical.

3.2.2.4 Jet sources

Figure 48 presents the comparison of jet source results from ADMS and AERMOD for agricultural sources.

Although the difference in the ADMS and AERMOD 'jet' source definitions makes a direct comparison between the models slightly inconsistent, it is still of interest to assess the difference in model behaviour for the case considered where both releases are wind aligned. For both models, the jet source definition is similar to the point source formulation, and previous studies have demonstrated that in flat terrain conditions in the absence of building effects, ADMS and AERMOD often behave in a similar manner.

For both ADMS and AERMOD, the maximum concentration decreases with increasing exit velocity due to increased entrainment; maximum concentrations decrease with increasing temperature due to increased plume rise.

ADMS models the jet release as a horizontal source close to ground level, with reasonably high efflux parameters. For both ADMS and AERMOD, the predicted ground-level concentrations are a combination of jet exit velocity, plume rise and plume spread, making it difficult to exactly explain the differences in model behaviour.

In terms of magnitude of ground level concentrations, AERMOD and ADMS predict similar values for the ambient, low exit velocity release, but concentrations diverge with increasing efflux magnitude; this is expected as ADMS and AERMOD use different methodologies for calculating plume rise:

- ADMS 5 integrates the mass, momentum and heat flux equations as the plume moves downstream; and
- AERMOD uses the Briggs formula to calculate an effective plume height.

Overall, AERMOD concentrations tend to be lower.

3.3 Annual runs

The sources have been modelled with a single year of meteorological data (Waddington, 2008)^{††}. In order to limit the number of results, the following input options have been considered:

- Source dimensions in terms of a 'high' or 'low' source and
- Source momentum and buoyancy in terms of a 'passive release' or 'buoyant release with initial momentum'.

Specific details of the parameter values selected are given in Table 23 for agricultural sources and Table 24 for bioaerosol sources. Source emission rates are the same as for the individual meteorological conditions (Table 19) and horizontal source dimensions were also consistent, specifically: the line source horizontal dimensions are 10 m by 1 m; the area and volume source dimensions are 60 m by 10 m and the jet source has a diameter of 1.2 m. Concentrations were modelled up to 10 km from the source, but as values decay rapidly near the source, only near-field results have been presented in the figures.

For the annual runs, both the average and maximum values calculated by the models are presented. Arcs of model receptor points were defined at radial distances from the source, as shown in Figure 5. The average results at a particular downwind distance are taken to be the average of all values on that arc; the maximum is taken to be the maximum of all values on the arc. The receptors are at ground level.

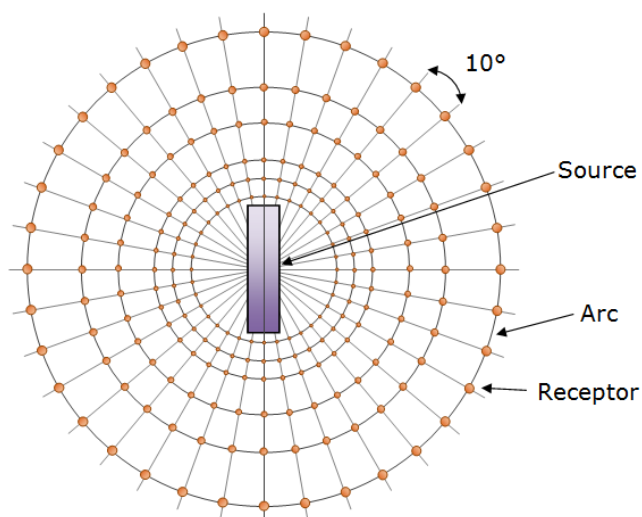


Figure 5 Receptor arc used for idealised modelling runs

^{††} Kindly licensed free of charge by Matthew Hort, Met Office (private communication, May 2015)

Table 23 Agricultural source parameter ranges for annual runs; *buoyant sources have non-zero initial momentum

Idealised source type	Case	Source dimensions (m)		Efflux parameters	
		Height	Depth	Temperature (°C)	Velocity (m/s)
Line	Passive line (low)	0		Ambient	0
	Passive line (high)	2	n/a	Ambient	0
	Buoyant* line (low)	0		Ambient + 10	0.1
	Buoyant* line (high)	2		Ambient + 10	0.1
Area	Passive area (low)	0		Ambient	0
	Passive area (high)	2	n/a	Ambient	0
	Buoyant* area (low)	0		Ambient + 10	0.1
	Buoyant* area (high)	2		Ambient + 10	0.1
Volume	Volume	1.875	3.75	Ambient	0
Jet	Passive jet	3	n/a	Ambient	0.5
	Buoyant* jet	3		Ambient +10	15

Table 24 Bioaerosol source parameter ranges for annual runs; *buoyant sources have non-zero initial momentum

Idealised source type	Case	Source dimensions (m)		Efflux parameters	
		Height	Depth	Temperature (°C)	Velocity (m/s)
Area	Passive area (low)	0		15	0
	Passive area (high)	5	n/a	15	0
	Buoyant*area (low)	0		35	2.95
	Buoyant*area (high)	5		35	2.95
Volume	Volume	1.875	3.75	Ambient	0

3.3.1 Results summary

The average and maximum results from the annual agricultural model runs for ADMS and AERMOD are presented in Figures 49 and 50 respectively; similarly, the average and maximum results from the annual bioaerosol model runs are presented in Figures 53 and 54 respectively. Note that these figures are presented using a log scale for the concentration values displayed on the vertical axes for all graphs apart from those showing the annual average jet source results.

In addition to these figures, where the results are presented separately for each source type, it is important to present the results for all source types together, in order to assess the influence of source definition on modelled concentrations. Figures 6 and 7 show the annual average and maximum concentrations from agricultural sources respectively; Figure 8 shows the corresponding information for bioaerosol sources.

3.3.2 Discussion

Figures 49 a), b) e) and f) showing the annual average concentrations from agricultural line and area sources up to 250 m downwind of the source for ADMS and AERMOD demonstrate that, in terms of the source elevations (the 'high' and 'low' cases) the models perform as expected, predicting higher ground level concentrations for the 'low' source. For ADMS, where buoyancy is modelled, the impact of buoyancy is also as expected i.e. the buoyant releases lead to lower concentrations compared to the non-buoyant releases.

As for the individual meteorological conditions, the volume source results appear very similar for ADMS and AERMOD. Further, there is no residue of the 'spiky' concentration profile in AERMOD from the single meteorological case in the annual average result, indicating that this near source feature is smoothed out for annual runs, and is consequently unimportant for the large majority of modelling work undertaken. The annual average ADMS and AERMOD jet source results shown in Figures 49 g) and h) indicate that the differing formulations of the 'jet' sources in these models has a large influence on results up to about 100 m. For both ADMS and AERMOD, the buoyant jet / horizontal point source predicts higher ground-level concentrations than the non-buoyant release; this is due to the increased entrainment generated by the buoyant release, which causes the plume to mix down to the ground.

The corresponding maximum concentration plots shown in Figure 50 show the same model behaviour as the average concentrations so are not discussed further here. The pattern is also similar for the bioaerosol sources, with the only real difference being that in this case the buoyant release leads to significantly lower concentrations (over a factor of ten at 100 m).

Figures 6 a) and c) show the annual average results from all representations of the agricultural source modelled in ADMS and AERMOD using a log scale up to 250 m downwind of the source. This plot shows that the different non-point source types result in very different in- and near-source concentrations. Figures 6 b) and d) show the corresponding information on a non-log plot, which allows the predicted concentrations downwind of the source to be assessed. Again, there is a wide range of ground-level concentration results. Figure 7 shows the corresponding information relating to maximum concentrations.

Although these plots indicate the overall range of concentrations relating to all source representations that the models are predicting, it is difficult to distinguish the behaviour of the different models and sources. Therefore, a more detailed figure showing the concentrations at a fixed distance downwind of the source has been presented in Figure 9, with the upper plot showing the annual average concentrations and the lower plot showing the maximum. These plots allow the following conclusions to be drawn relating to predicted model concentrations at distances of 100 m downwind of an agricultural source:

- If buoyancy effects are unimportant, it makes little difference whether the source is modelled as a line, area or volume source in either ADMS or AERMOD, *if* the source is modelled at a few metres above the ground.

- If the source is modelled as a ground-level line or area source, AERMOD predicts much higher concentrations than ADMS (a factor of two higher for the annual average, and a factor of five higher for the maximum concentrations)^{††}.
- When buoyancy effects are included in ADMS, for line and area sources, annual average concentrations are up to 50% lower than without buoyancy for a line source, and between 50 and 75% lower for an area source.
- Concentrations are lower when the release is modelled using a jet source compared to all the other source configurations; this is due to the higher exit velocities used for this source type (15 m/s and 0.5 m/s for the buoyant and non-buoyant sources respectively), which have been selected to represent the release from a mechanically ventilated fan on the side of building. AERMOD predicts lower concentrations than ADMS for both the buoyant and non-buoyant horizontal jet source.

Figures 8 a) and c) show the annual average results from all representations of the bioaerosol source modelled in ADMS and AERMOD using a log scale up to 250 m downwind of the source. This plot shows that the different non-point source types result in a range of in and near-source concentrations, although the results from low non-buoyant area sources are similar to those from volume sources. Figures 8 b) and d) show the corresponding information relating to maximum concentrations.

These plots show that the different source representations for bioaerosol sources result in predicted modelled concentrations that vary by one or two orders of magnitude. As would be expected, when the buoyancy and initial momentum of the release is modelled using, for example, Philippa Douglas' (Douglas, 2013) suggested value, the concentrations are much lower. As for agricultural sources, a more detailed figure showing the concentrations at a fixed distance downwind of the source has been presented in Figure 10, with the upper plot showing the annual average concentrations and the lower plot showing the maximum. These plots allow the following conclusions to be drawn relating to predicted model concentrations at distances of 100 m downwind of a bioaerosol source:

- If buoyancy effects are unimportant:
 - ADMS and AERMOD predict similar concentrations if the source is modelled as an elevated area or a volume source.

^{††} As the authors were unable to explain this discrepancy between ADMS and AERMOD predicted concentrations for low level line sources, the AERMOD developers were contacted asked to comment on this model behaviour. The response included a statement agreeing with the conclusions reached by the authors i.e. that modelling a ground level release using the default initial vertical plume spread parameter of 0 m leads to very large predicted concentrations.

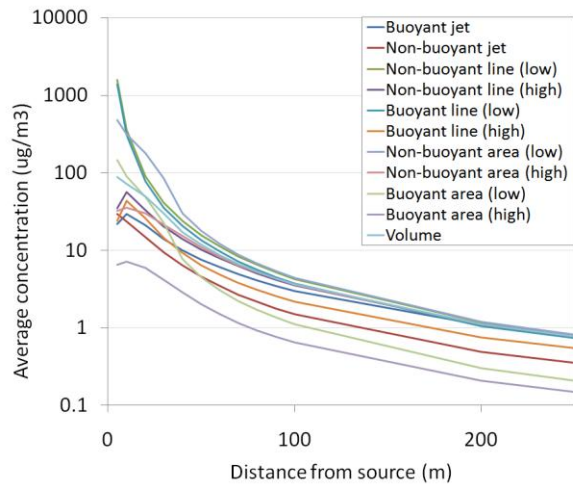
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- In ADMS, modelled concentrations are similar if the source is modelled as a low-level area source or a volume source; modelling as an elevated area source reduces predicted concentrations at the ground-level receptors.
 - In AERMOD, modelling the source as a low-level area source leads to higher predicted concentrations than a volume source; using an elevated area source gives lower concentrations than a volume source.
 - When buoyancy effects are included in ADMS, for area sources, annual average and maximum concentrations are between 10 and 50 times lower than without buoyancy.

As the model behaviour at 100 m downwind of the source is reasonably representative of concentrations in the mid-field, the overall conclusions here are that:

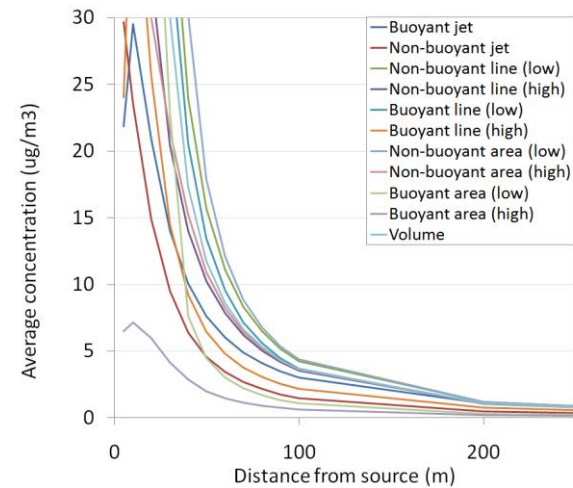
1. For agricultural sources, if buoyancy is unimportant, it makes little difference whether the source is modelled as a volume source, or an elevated line or area source, and ADMS and AERMOD give similar results.
2. ADMS and AERMOD predictions for ground-level sources differ, with AERMOD predicting higher concentrations than ADMS.
3. When buoyancy is accounted for in ADMS for line and area sources, concentrations are much lower, particularly for bioaerosol sources.

Having quantified the difference in model behaviour for the different source types and models, the aim of the next section is to assess how well these sources represent real-world conditions.

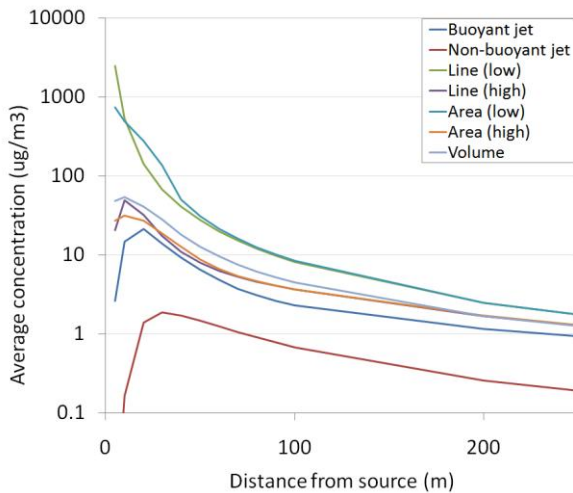
a) ADMS results showing near-source concentrations (log scale)



b) ADMS results showing mid-field concentrations



c) AERMOD results showing near-source concentrations (log scale)



d) AERMOD results showing mid-field concentrations

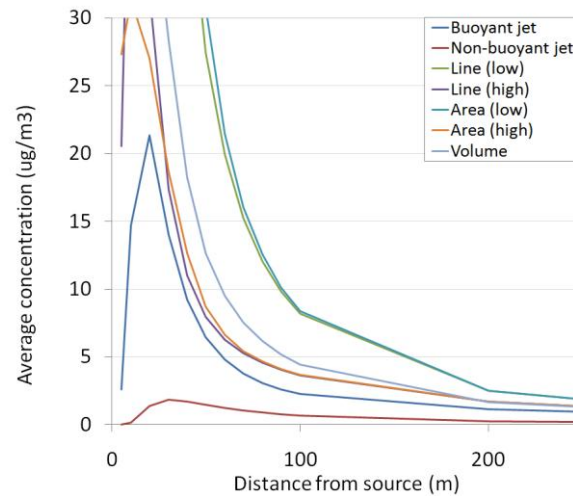
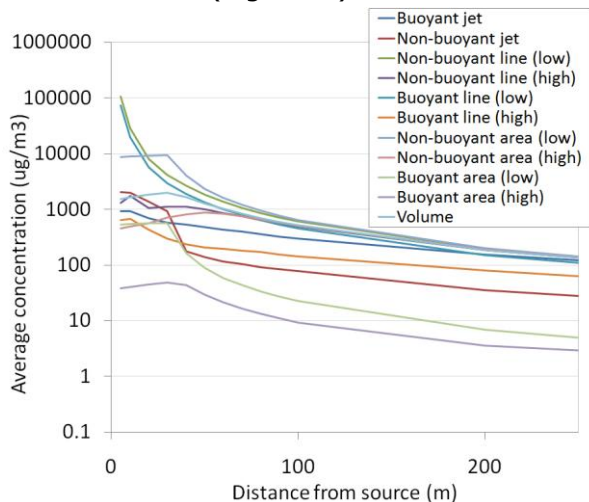
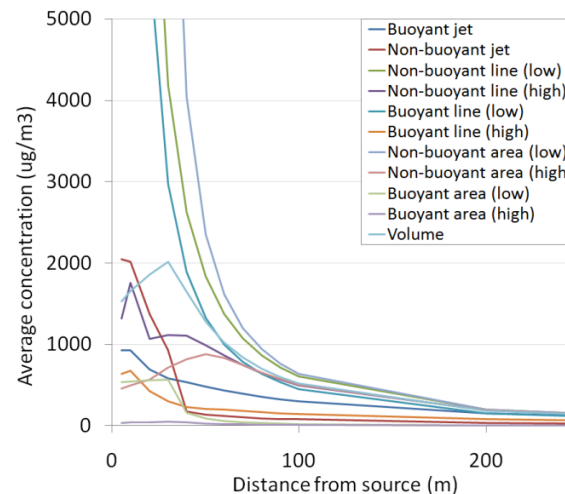


Figure 6 Average annual average concentrations from ADMS and AERMOD for agricultural sources

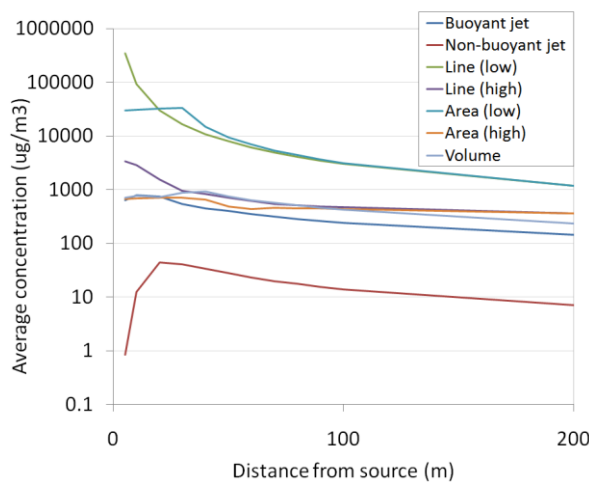
a) ADMS results showing near-source concentrations (log scale)



b) ADMS results showing mid-field concentrations



c) AERMOD results showing near-source concentrations (log scale)



d) AERMOD results showing mid-field concentrations

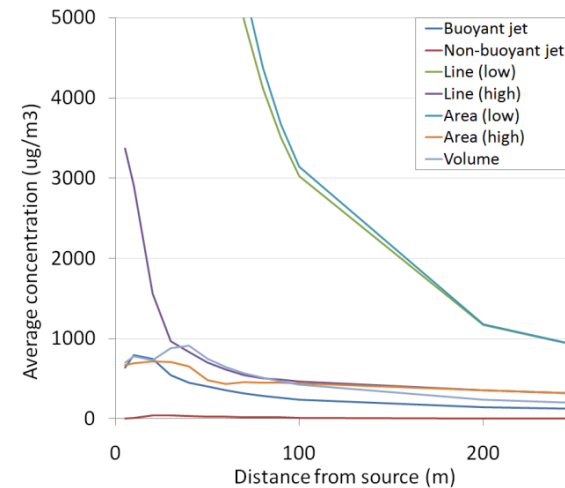
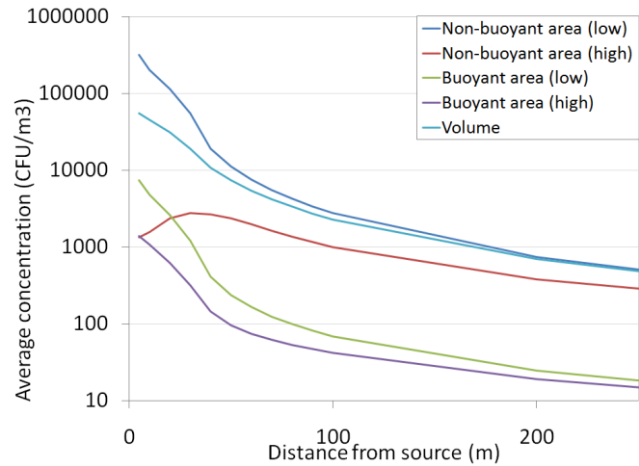
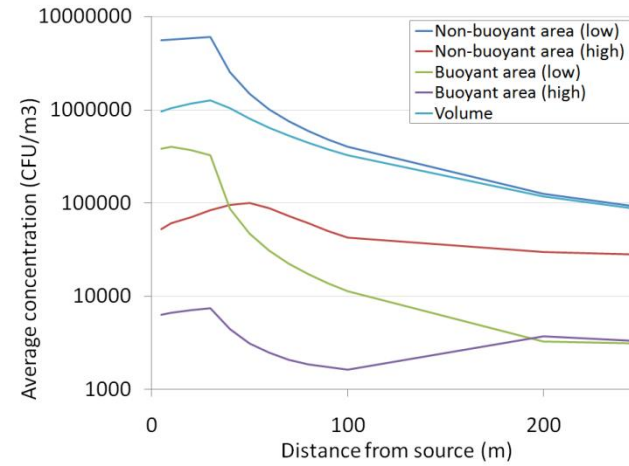


Figure 7 Maximum annual average concentrations from ADMS and AERMOD for agricultural sources

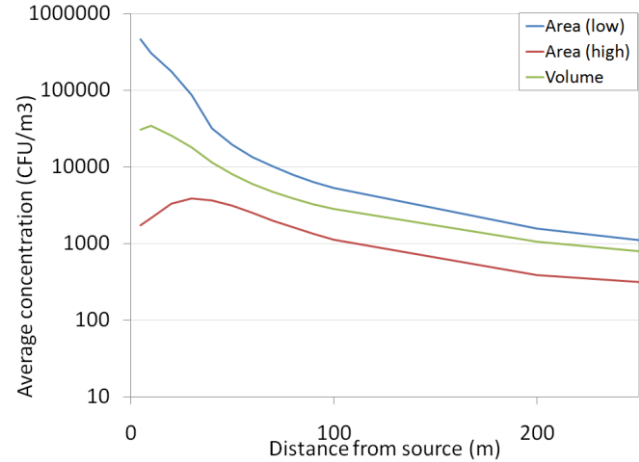
a) Average ADMS results showing near-source concentrations (log scale)



b) Maximum ADMS results showing mid-field concentrations



c) Average AERMOD results showing near-source concentrations (log scale)



d) Maximum AERMOD results showing mid-field concentrations

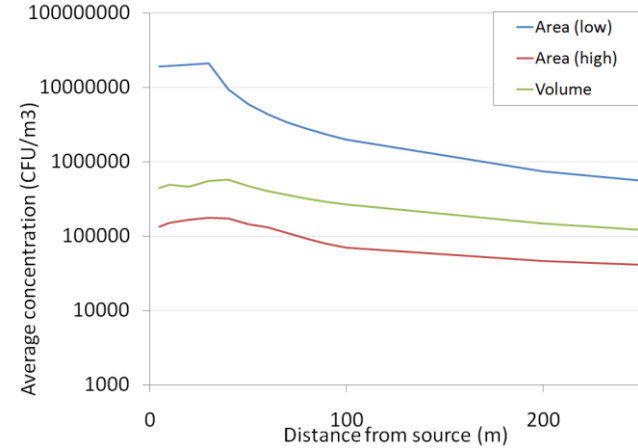


Figure 8 Average and maximum annual average concentrations from ADMS and AERMOD for bioaerosol sources

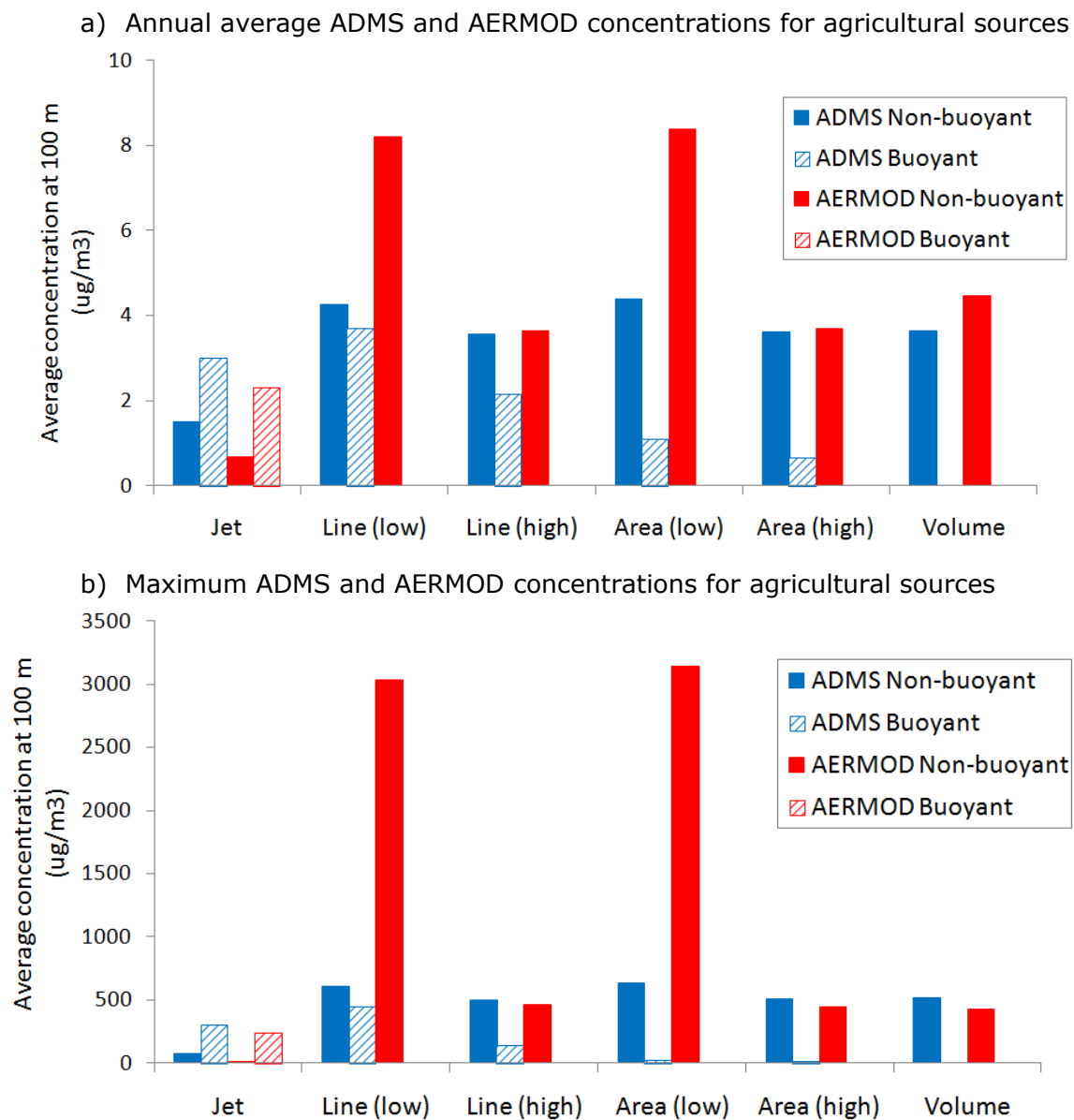


Figure 9 Comparison of concentrations predicted by ADMS and AERMOD at 100 m downwind of an agricultural source a) annual average and b) maximum values; note that AERMOD does not model buoyancy for line and area sources and neither ADMS nor AERMOD model buoyancy for volume sources.

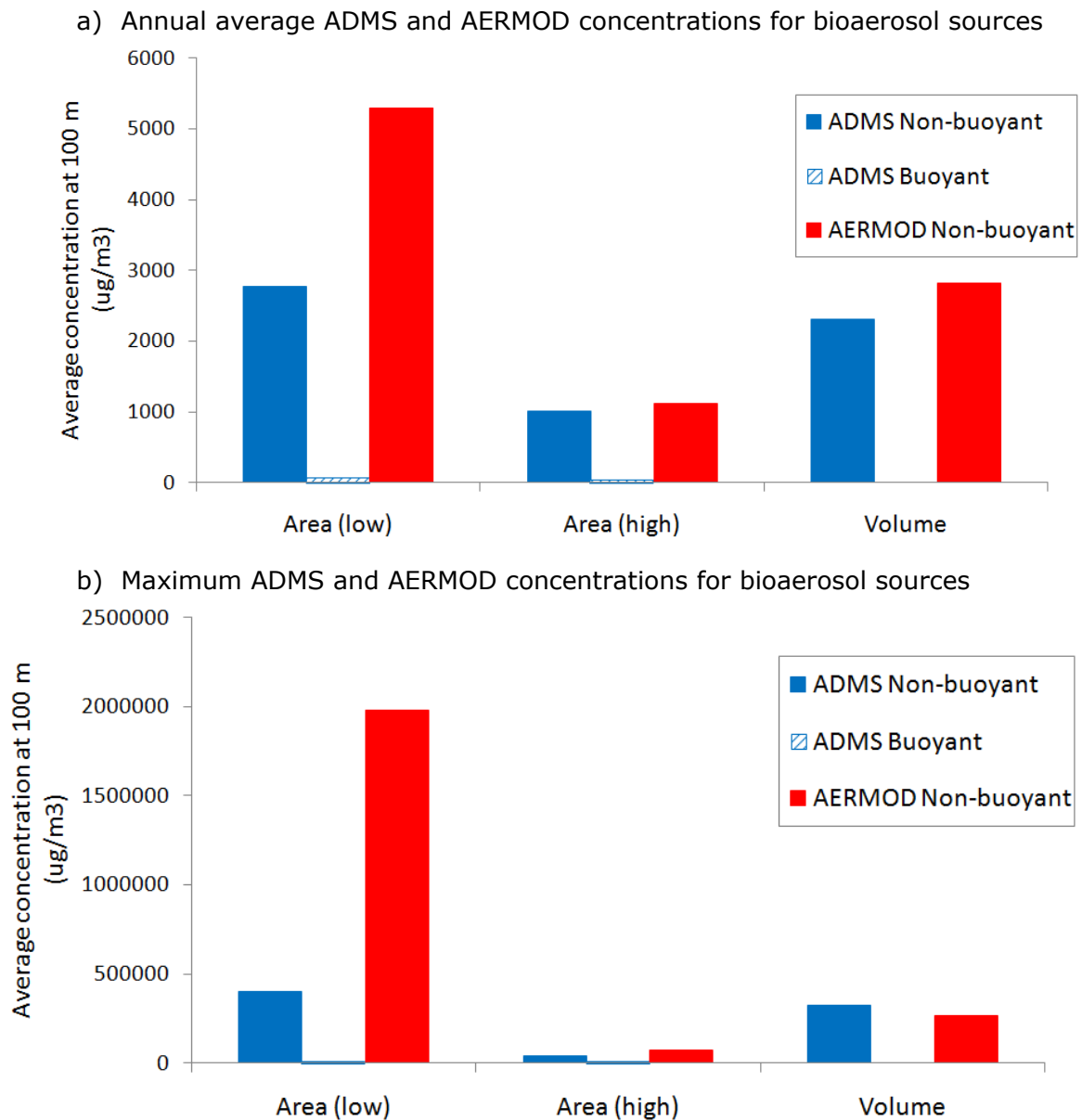


Figure 10 Comparison of concentrations predicted by ADMS and AERMOD at 100 m downwind of a bioaerosol source a) annual average and b) maximum values; note that AERMOD does not model buoyancy for area sources and neither ADMS nor AERMOD model buoyancy for volume sources.

4 TASK 3: MODEL EVALUATION

4.1 Overview

The models have been set up to represent the case studies for which data were obtained during the literature review, as discussed in Section 2.6. In an attempt to assess the variation in predicted concentrations associated with different source configurations, a full range of non-point source types has been used for each model evaluation exercise; specifically: agricultural releases have been represented using jet, line, area and volume sources, and bioaerosol releases using area and volume. In addition, point sources have been modelled with, and in some cases without, a building for comparison with the non-point agricultural source type releases. In reality, some of the source types used for the model evaluation exercise are not wholly appropriate for the real-world sources under consideration.

There are uncertainties associated with all the datasets. The greatest uncertainties relate to the meteorological data and source term assumptions, including the emission rates and efflux parameters. The Whitelees dataset is the most robust out of those considered, as it includes almost 3 months of continuously measured ammonia concentrations; this is in addition to odour measurements and a set of period-average ammonia samples which can be used to support any conclusions drawn.

Each of the datasets comprised different data, in particular the observed data were recorded using a range of time periods. For instance, the odour measurements at Whitelees are 10-minute averages, whereas some of the ammonia alpha sampler measurements at that location are for periods of nearly a month. The Defra poultry farm measurements are for 'light' and 'dark' periods during the day, and the Defra bioaerosol data measurements were for 30 and 45 minute intervals. Consequently, for each case study, the modelling has been performed using averaging times that correspond to the measured data, and the model analyses and methods used to compare model results to the observations differ.

Fan exit concentrations and ventilation rates were measured for the three poultry farm studies, although for Farm F, an estimate for the ventilation rate was used, as the measured value appeared inaccurate. The emission rates derived from these measurements have been compared to those given in Appendix 1 of the Environment Agency intensive farming guidance note (EA, 2013) in the sections given below.

The ammonia measurements made at Whitelees were restricted to concentration rather than deposition. It would be possible to investigate the impact of modelling deposition on atmospheric ammonia concentrations, but in the absence of corresponding deposition measurements, it would be difficult to draw conclusions. Consequently, the influence of ammonia deposition has not been included in this study.

For the Whitelees study, where continuous monitoring data are available, the model results have been analysed using CERC's MyAir Model Evaluation Toolkit. This tool calculates a range of values including: the number of valid observations, the observed and modelled mean concentrations, normalised mean square error (NMSE), correlation coefficient (R), fraction of modelled values within a factor of two of the observed (Fac2) and the index of agreement^{§§} (IoA). In addition to statistics relating to average values, the observed and modelled maximum and robust highest concentrations^{***} (RHC) have been calculated.

For the shorter-term measurements at Whitelees and for the other studies, where the observation data are not recorded at a sufficiently high temporal resolution to justify detailed statistical analyses, results have been presented graphically.

As discussed in the literature review, the dispersion modelling of bioaerosol sources is particularly challenging, as there are many uncertainties associated with the source term, for example: there is poor understanding of the structure of the 'plume' released from some bioaerosol sources, particularly during activities such as shredding and turning of windrows; emissions are highly variable and difficult to estimate; source temperatures are variable; and there are limitations associated with the measurements of some species emanating from these sources. Consequently, there have been a number of simplifications in the methodology used for the bioaerosol model evaluation exercise.

In terms of reaching conclusions relating to model behaviour from these model evaluation exercises, for the cases where the releases have buoyancy and initial momentum, it is of interest to know whether it is the buoyancy or the momentum that most influences plume rise. To this end, buoyancy and momentum flux calculations have been performed for each of the studies, using the methodology given in the ISC3 User Guide (ISC3, 1995); for reference, a summary of this methodology is given in APPENDIX E.

Section 4.2 presents the results from modelling the Whitelees Farm; Sections 4.3 and 4.4 give the results from Farm F and Farm G respectively from the Defra poultry datasets and Section 4.5 gives the results from the Defra bioaerosol study.

^{§§} The Index Of Agreement (IOA) spans between -1 and +1, with values approaching +1 representing better model performance.

^{***} Taken to be $\chi(n) + (\chi - \chi(n)) \ln\left(\frac{3n-1}{2}\right)$ where n is the number of values used to characterise the upper end of the concentration distribution, χ is the average of the $n - 1$ largest values, and $\chi(n)$ is the n^{th} largest value; n is taken to be 26.

4.2 Whitelees Farm

4.2.1 Site configuration and emissions

The Whitelees Farm poultry house site is located in South Lanarkshire, Scotland, 3 km to the northeast of Lanark. The site houses approximately 37 000 layers.

The site comprises four identical rectangular sheds, closely spaced and aligned parallel to each other. Each shed is divided into two buildings; each building is ventilated through a series of ten fan-assisted cowls pointing upwards at a 45° angle on each long side, giving a total of 80 vents on the site. The vents are similar in design to those at Glendevon (shown in Figure 11).



Figure 11 Upward pointing cowl at Glendevon Farm; figure taken from Hill *et al.* (2014), reproduced here with permission from Sniffer (private communication, 05/08/15).

Volume flow rates, ammonia concentrations and odour concentrations were measured at a number of vents across the site on the 19th September 2013, and the 26th September 2013. There was quite significant variation in the volume flow rates on a vent-by-vent basis, with the measured values varying between 1.0 m³/s and 2.6 m³/s within a few hours. However, as data were not available to model the exact variation, a total volume flow rate from the site was calculated by using an average volume flow rate per building based on the number of vents operating; when data were unavailable for a building, the average flow rate for the other buildings was used. A total emission rate for the site was calculated using the average measured emission concentration per building, and this flow rate. Table 25 summarises the emissions parameters used for the study.

The suggested ammonia emission rate for layers housed in sheds such as those at Whitelees is 0.29 kg NH₃/animal/year (EA, 2013). The measurements at Whitelees result in a higher value of 0.84 kg NH₃/animal/year. The discrepancy between the recommended value and the measured value for this study is likely

to be related to the variation in emissions due to the stage in the cycle, although there may be inaccuracies in the measured fan exit concentrations and ventilation rates.

Performing buoyancy and momentum flux calculations in line with the methodology given in the ISC3 document (APPENDIX E) indicates that for average meteorological and exit conditions, plume rise is driven by the initial momentum flux; in cold meteorological conditions, the initial buoyancy flux has more effect.

Table 25 Calculated emissions parameters for the Whitelees farm site

Modelling period	Total volume flow rate, m ³ /s	Total NH ₃ emission rate, g/s	Total odour emission rate, ou _E /s
19/09/2013	55.8	0.86	14740
26/09/2013	49.5	1.10	14120
Whole period	52.7	0.98	14470

4.2.2 Measurements

An overview of the Whitelees Farm campaign is given in Section 2.6.1 and full details are given in Hill *et al.* (2014). For model verification, three datasets from the campaign were used:

- Continuous ammonia monitoring, carried out at a single station approximately 60 m to the north of the farm;
- Fixed-period ammonia monitoring using Alpha Samplers at 9 sites surrounding the farm; and
- Odour measurements recorded on transects on the 19th of September. 'Sniffers' measured odour levels for a ten minute period within each hour at each location. Additional measurements were made on the 26th of September, but the measurements on that day suggest that no plume was captured.

An aerial view of the site showing the location of the continuous monitoring locations and Alpha sampler locations is given in Figure 12 below. The odour measurements used for model evaluation were recorded on transects such as those shown in Figure 13.

Vent flow and concentration data were measured on the 19th September 2013 and the 26th September 2013. On these two days, a maximum of 4 vents operated per building; full spatial information for the operating vents was not supplied.



Figure 12 Whitelees Farm study area showing location of the onsite meteorological station (White 1) which is co-located with the continuous ammonia monitoring equipment; White 2 to White 9 indicate the locations of additional ammonia measurements; figure taken from Hill *et al.* (2014), reproduced here with permission from Sniffer (private communication, 05/08/15).

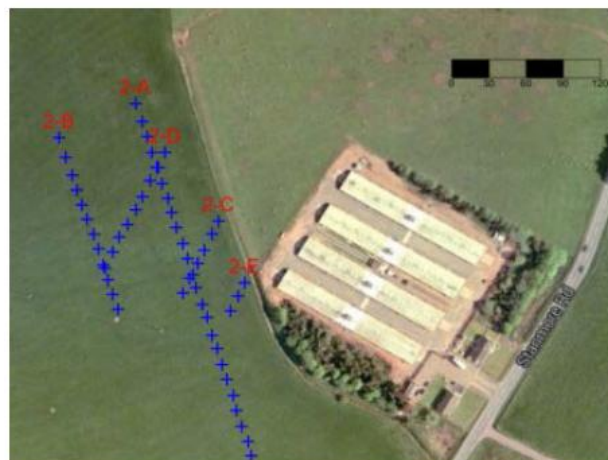


Figure 13 Location of deployment of odour monitoring on 26th September 2013; figure taken from Hill *et al.* (2014), reproduced here with permission from Sniffer (private communication, 05/08/15).

Figure 14 shows the time series of the continuously monitored hourly ammonia concentrations. This figure displays the considerable decrease in measured concentrations when the poultry are removed from the shed, towards the end of October. Figure 15 shows the variation of the continuously monitored ammonia concentrations with wind direction. This figure shows the clear signature of the release from the farm recorded at the monitor; the background ammonia concentrations are in general small. These simple analyses indicate that the continuous ammonia monitoring undertaken at Whitelees constitutes a robust dataset appropriate for use in a dispersion model evaluation study.

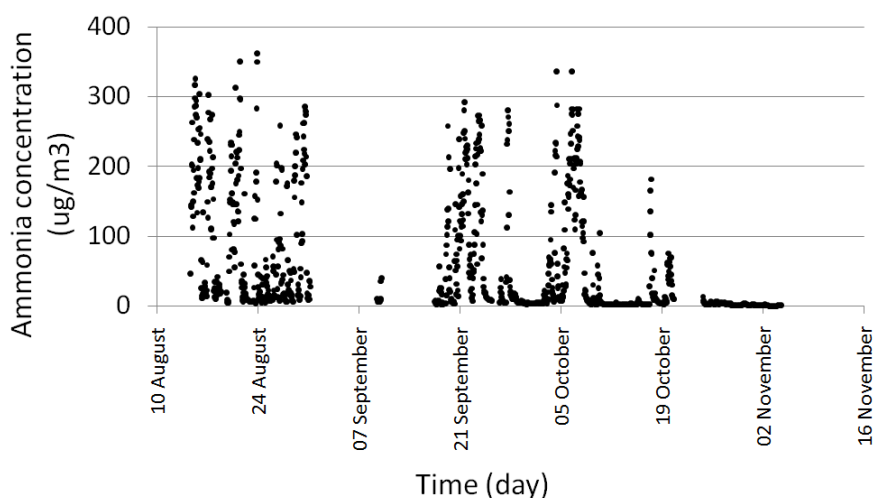


Figure 14 Time series of showing hourly observed continuously monitored ammonia concentrations for the Whitelees Farm study

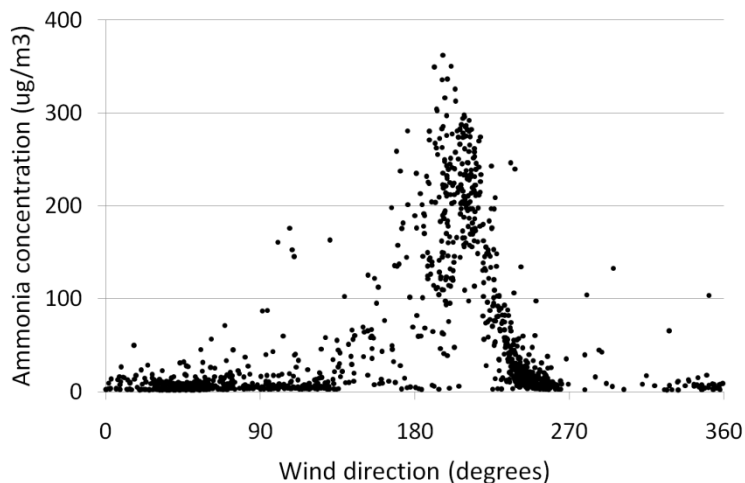


Figure 15 Hourly observed ammonia continuously monitored concentrations against wind direction for the Whitelees Farm study (up to 20th October)

Monitored time-integrated NH₃ concentrations were measured using passive diffusion Alpha samplers for 4 periods on an approximately monthly frequency. The periods of the monitoring are presented in Table 26.

Table 26 Alpha sampler monthly ammonia modelling periods

Run	Start (GMT)	End (GMT)	Duration (days)
Run 1	06/08/2013 13:00	29/08/2013 12:00	23
Run 2	05/09/2013 12:00	02/10/2013 12:00	27
Run 3	02/10/2013 12:00	14/10/2013 12:00	12
Run 4	21/10/2013 13:00	04/11/2013 12:00	14

4.2.3 Model set up

4.2.3.1 Source configurations and efflux parameters

When modelling a poultry house, it is standard practice to model a representative subset of sources on the building; this approach has been taken for the current study using a number of source configurations. Figure 16 shows the horizontal representation of each source type (point, jet, volume, area and line) used to model the release.

A generalised modelling approach has been taken: single area and volume sources have been used to model all four sheds, and the line sources have been located to approximate the location of the side vents on the outer walls of the sheds.

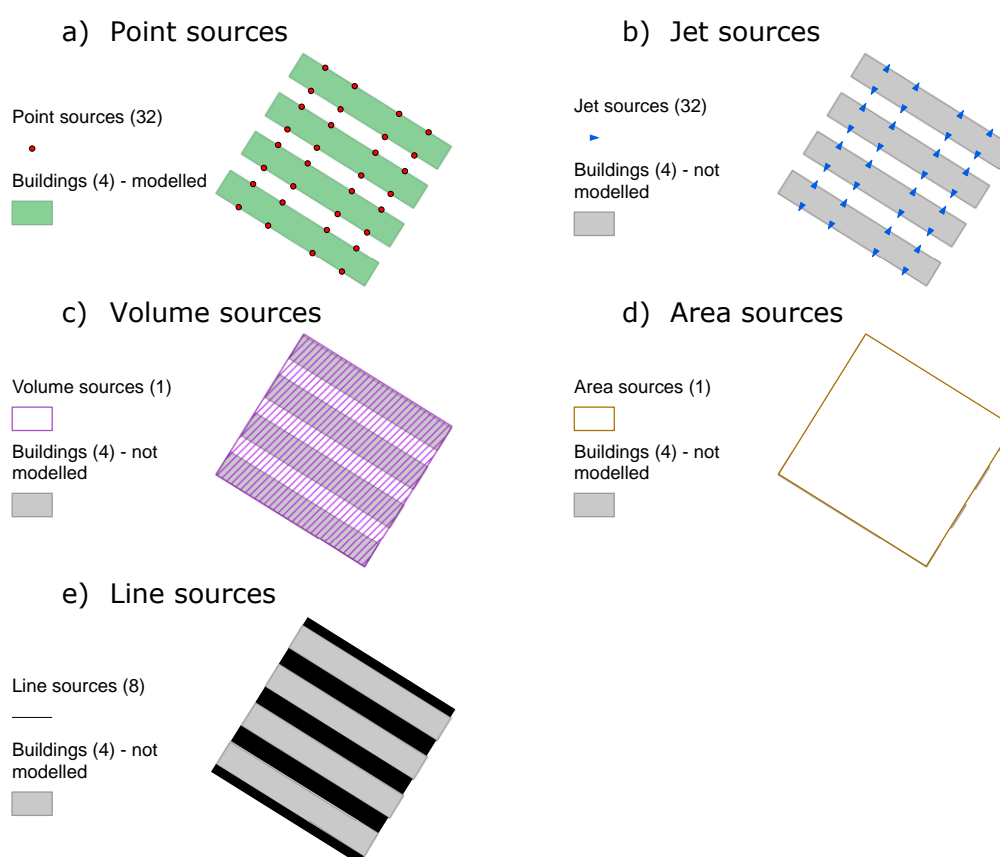


Figure 16 Source representations for Whitelees Farm; buildings explicitly modelled with point sources only

For the purposes of modelling, 4 vents were assumed to operate per building, with two vents evenly spaced along each side, giving a total of 32 vents operating across the site. This approach is used because, whilst it is possible to model each vent explicitly, release data are not available on a vent-by-vent basis for the full period. Modelling a limited number of sources reduces model set up time and the approach is sufficiently accurate because the vents are evenly distributed. Further, on the 19th and 26th September, there were only 4

vents operating at the majority of the sheds from which volume flow rate and emissions measurements were taken.

The parameters for the modelled buildings are presented in Table 27. Each shed was modelled as a separate building. Note that building effects can only be included when modelling the site as point sources; as a result, the other source configurations do not include modelled buildings.

Table 27 Building parameters used in point sources configuration

Name	Location (x,y)	Height (m)	Length (m)	Width (m)	Angle (°)
EX1	291301, 646391	4	14.5	94.3	32.0
EX2	291315, 646412	4	14.5	94.3	32.0
EX3	291327, 646433	4	14.5	94.3	32.0
EX4	291340, 646454	4	14.5	94.3	32.0

Emissions and volume flow rates for each source were calculated by dividing the total site emissions and total volume flow rate equally between the shed walls represented in the modelling, and, for the point and jet source configurations, equally between the sources representing each wall. Exit velocities were calculated corresponding to these volume flow rates. Using a constant emission rate is an approximation because ammonia and odour emissions are likely to increase due to the build up of manure within the shed during the lifetime of a flock.

For modelling the odour concentrations (19th September), average emissions and volume flow rates for that particular day were used. For modelling longer periods (i.e. to predict ammonia concentrations), the average parameters measured across the campaign were used. For point, line, and area sources, the vertical component of the calculated exit velocity was used as the modelled exit velocity in order to accurately model plume rise. Tables 28 and 29 present the modelled parameters for the ammonia and odour modelling respectively.

Table 28 Whitelees farm source parameter ranges, ammonia modelling; *ADMS only, AERMOD jet sources are wind aligned

Idealised source type	Source dimensions (m)			Efflux parameters	
	Height (m)	Diameter (m) / Dimensions: Length (m) x Width (m) (x depth, m)	Elevation angle to horizontal*	Temperature (°C)	Velocity (m/s)
Point	2	0.72	n/a	17.4	2.8
Jet*	2	0.72	45°	17.4	4.0
Volume	2	94 x 90 (x 2)	n/a	n/a	n/a
Area	2	94 x 90	n/a	17.4	0.0062
Line	2	94 x 5	n/a	17.4	2.8

Table 29 Whitelees farm source parameter ranges, odour modelling; *ADMS only, AERMOD jet sources are wind aligned

Idealised source type	Source dimensions (m)			Efflux parameters	
	Height (m)	Diameter (m) / Dimensions: Length (m) x Width (m) (x depth, m)	Elevation angle to horizontal*	Temperature (°C)	Velocity (m/s)
Point	2	0.72	n/a	17.4	3.0
Jet*	2	0.72	45°	17.4	4.2
Volume	2	94 x 90 (x 2)	n/a	n/a	n/a
Area	2	94 x 90	n/a	17.4	0.0066
Line	2	94 x 5	n/a	17.4	3.0

For line sources, the line width was taken to be the distance between the sheds, 10 m, to represent mixing effects in the narrow gaps. For line sources on the edges of the site complex, half this width was used.

As the cowls are attached to the sheds, downwash effects on the site will be dominated by building downwash. ADMS is able to model both building and stack downwash independently. Stack downwash has been disabled for this study, as including it in the modelling would over predict the downwash effects.

4.2.3.2 Meteorological data

The meteorological data measured at an onsite automatic weather station were recorded at 30 minute intervals and then averaged to derive hourly values for use in the modelling⁺⁺⁺. Data were provided for the period between the 14th August 2013 and the 4th November 2013 and these data were used to define the period over which the continuous monitor evaluation was performed. The met data do not cover all of the alpha sampler monthly ammonia modelling periods (Table 26); specifically, 'Run 1' was excluded from the modelling. A summary of the data used is given in Table 30. A wind rose giving the frequency of occurrence of wind from different directions for a number of wind speed ranges is presented in Figure 17.

Table 30 Meteorological statistics

Parameter	Minimum	Maximum	Mean
Temperature, °C	-1.6	19.6	10.7
Wind speed, m/s	0.6	22.6	6.6
Cloud cover, oktas	0	8	5.5
Relative humidity, %	51.8	96.2	85.0

⁺⁺⁺ This processing was performed by the data providers

A surface roughness length is used in the model to characterise the surrounding area in terms of the effects the parameter has on wind speed and turbulence, which are key components of the modelling. A value of 0.2 m has been used in this assessment, to represent the predominantly open area around the site. Ideally, sensitivity analyses assessing the dependence of model results on the value of roughness length would be performed, for instance a higher roughness length may be appropriate to represent the presence of the buildings, as they are not modelled explicitly with non-point source types. Unfortunately, it was not possible to do such analyses due to project constraints.

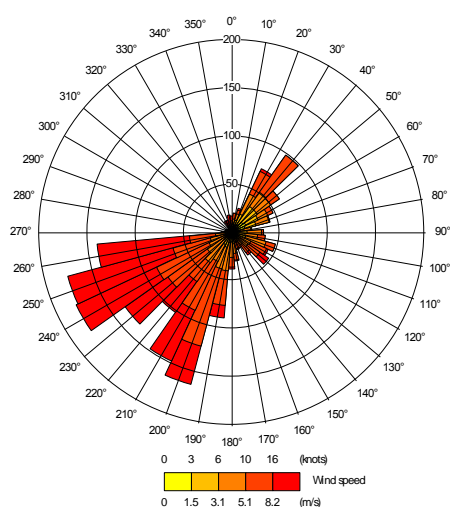


Figure 17 Wind rose for 14th August to 3rd October 2013 (continuous ammonia monitoring duration)

4.2.3.3 Output locations and settings

Figure 18 shows the receptor locations, i.e:

- the continuous ammonia measurement location, to the north-east of the buildings;
- the locations of the nine ammonia monitors used for four monthly sampling periods (shown in Figure 12), which are located at distances up to half a kilometre from the buildings, in various directions; and
- the 'downwind' transects where 10-minute odour measurements were taken; the numbers indicated on this figure correspond to each receptor location.

Only one set of odour transects was modelled, from the 19th September 2013. This was because on the second day (26th September 2013), the measurements did not reflect the presence of a plume, suggesting no plume capture took place.

In ADMS it is possible to vary the averaging time in the model. As the monitored odour measurements were taken over 10-minute periods, a 10-minute value was chosen; in AERMOD the averaging time is fixed at one hour. For the continuous and shorter-term ammonia monitoring, an averaging time of one hour was used in both models.

Receptors were located at 1.5 m above ground level.

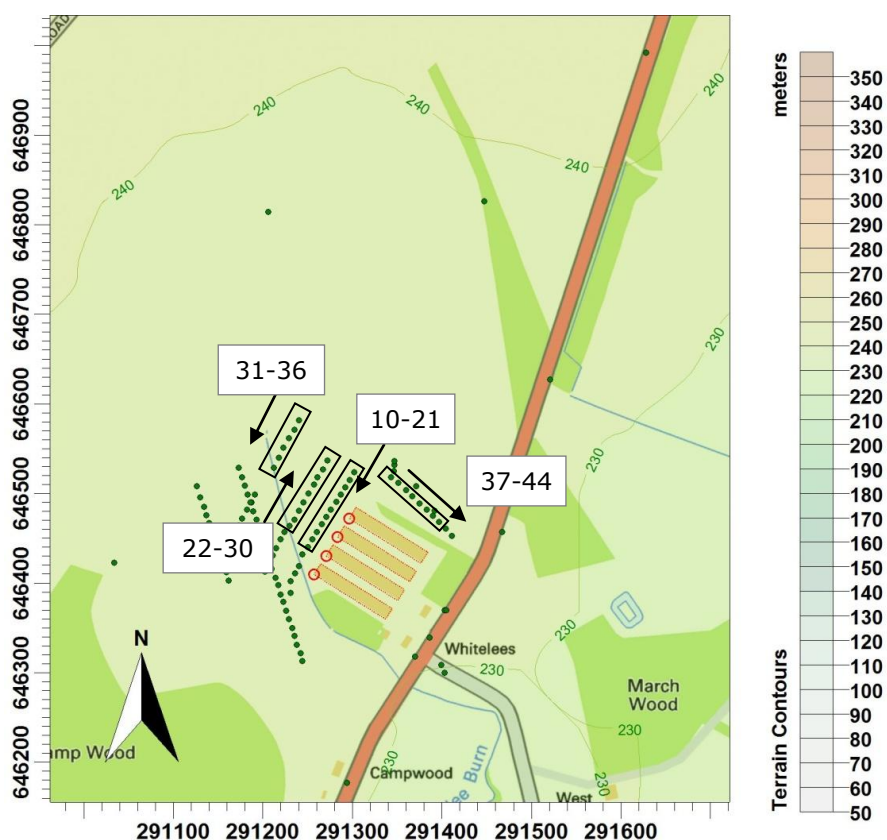


Figure 18 Study set up for Whitelees Farm showing buildings (orange rectangles) and receptors (dark green dots); receptor numbers and arrows show the locations of odour measurements on 19th of September; background map courtesy of © Crown copyright and database rights, 2015.

4.2.4 Results

4.2.4.1 Continuous ammonia monitoring

Hourly average ammonia concentrations were calculated at the location of the continuous monitor for comparison with measured values, from the 14th August 2013 to the 3rd October 2013.

For the continuous monitoring ammonia results, comparisons between observations and modelled values are restricted to the wind sector 150° to 250° (as indicated by Figure 14), and observations greater than 1 µg/m³; this limit is greater than the sampler detection limit (0.1 µg/m³) but sufficiently low to allow for all valid measurements. Furthermore, where results are presented on a log scale, the modelled results presented are also restricted to be greater than 1 µg/m³.

Tables 31 and 32 show the model evaluation statistics for Whitelees, in terms of average values; Tables 33 and 34 present the maximum values. Figure 19 shows the frequency scatter plots comparing ADMS modelled against observed hourly

average ammonia concentrations for area, jet, line, point and volume sources and Figure 21 shows the corresponding area, line, point and volume source results from AERMOD. These plots are shown using a log scale in order to show the full range of values. The ADMS and AERMOD results are also presented as quantile-quantile plots in Figures 20 and 22.

Table 31 Model evaluation statistics for Whitelees: ADMS average values

Source type	Statistic					
	<i>Obs. Mean</i> ($\mu\text{g}/\text{m}^3$)	Mod. mean ($\mu\text{g}/\text{m}^3$)	NMSE	R	Fac2	IoA
Area	119	67	0.97	0.66	0.41	0.61
Jet	119	96	0.60	0.63	0.53	0.65
Line	119	104	0.90	0.52	0.52	0.60
Point	119	87	1.07	0.47	0.41	0.57
Volume	119	163	7.54	0.18	0.48	0.26

Table 32 Model evaluation statistics for Whitelees: AERMOD average values

Source type	Statistic					
	<i>Obs. Mean</i> ($\mu\text{g}/\text{m}^3$)	Mod. mean ($\mu\text{g}/\text{m}^3$)	NMSE	R	Fac2	IoA
Area	119	193	13.0	0.14	0.44	0.05
Line	119	197	13.1	0.14	0.44	0.03
Point	119	149	1.8	0.48	0.43	0.47
Volume	119	147	9.7	0.15	0.34	0.19

Table 33 Model evaluation statistics for Whitelees: ADMS maximum values

Source type	Statistic ($\mu\text{g}/\text{m}^3$)			
	<i>Obs. maximum</i>	Mod. maximum	<i>Obs. RHC</i>	Mod. RHC
Area	362	388	367	390
Jet	362	445	367	479
Line	362	961	367	808
Point	362	872	367	808
Volume	362	3997	367	4274

Table 34 Model evaluation statistics for Whitelees: AERMOD maximum values

Source type	Statistic ($\mu\text{g}/\text{m}^3$)			
	<i>Obs. maximum</i>	Mod. maximum	<i>Obs. RHC</i>	Mod. RHC
Area	362	5647	367	6065
Line	362	5660	367	6188
Point	362	1761	367	1618
Volume	362	4785	367	4442

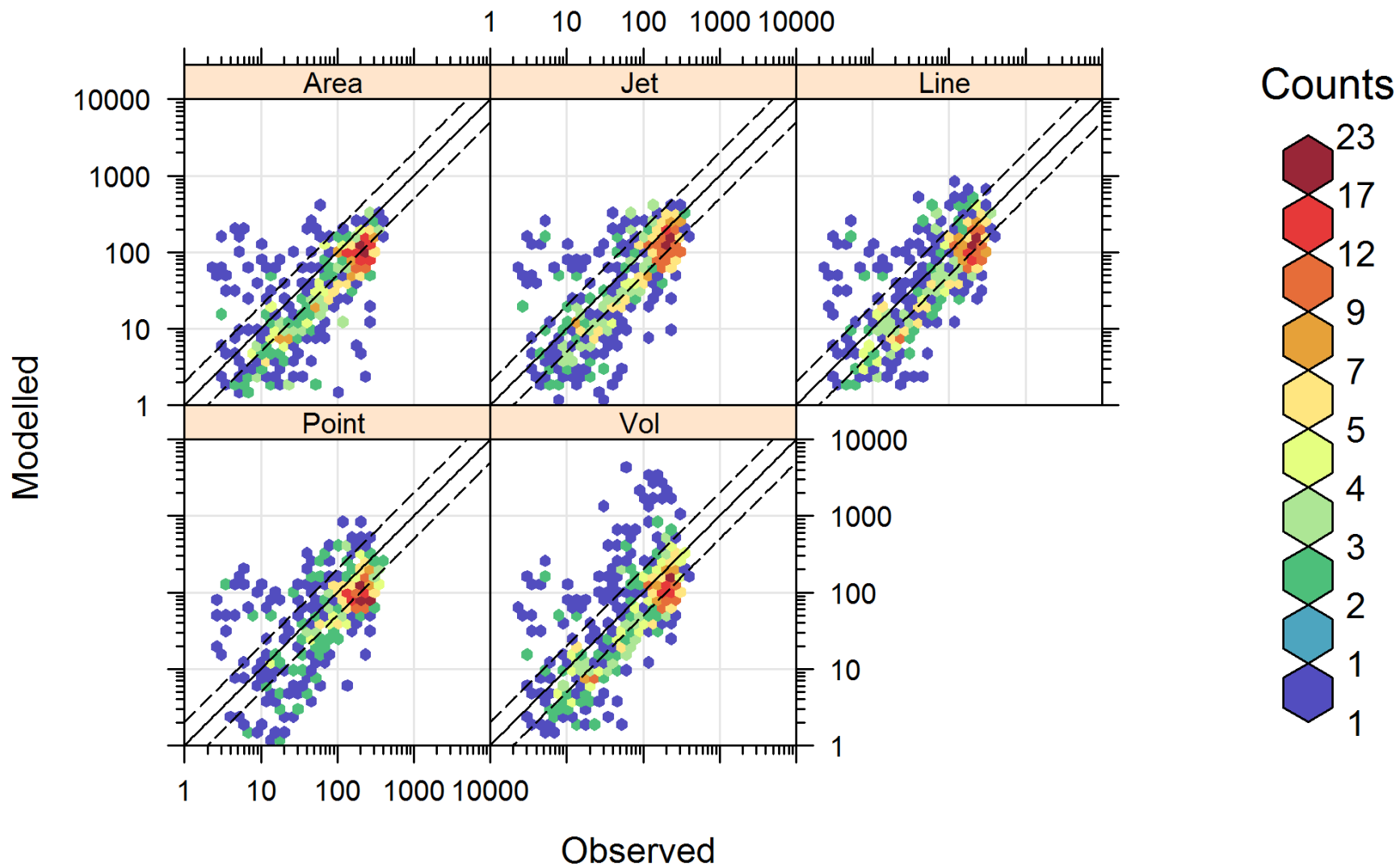


Figure 19 Frequency scatter plots, comparing ADMS modelled against observed hourly average ammonia concentrations ($\mu\text{g}/\text{m}^3$) recorded at Whitelees farm for area, jet, line, point and volume sources; wind directions between 150° and 250° , observations & modelled values $> 1 \mu\text{g}/\text{m}^3$

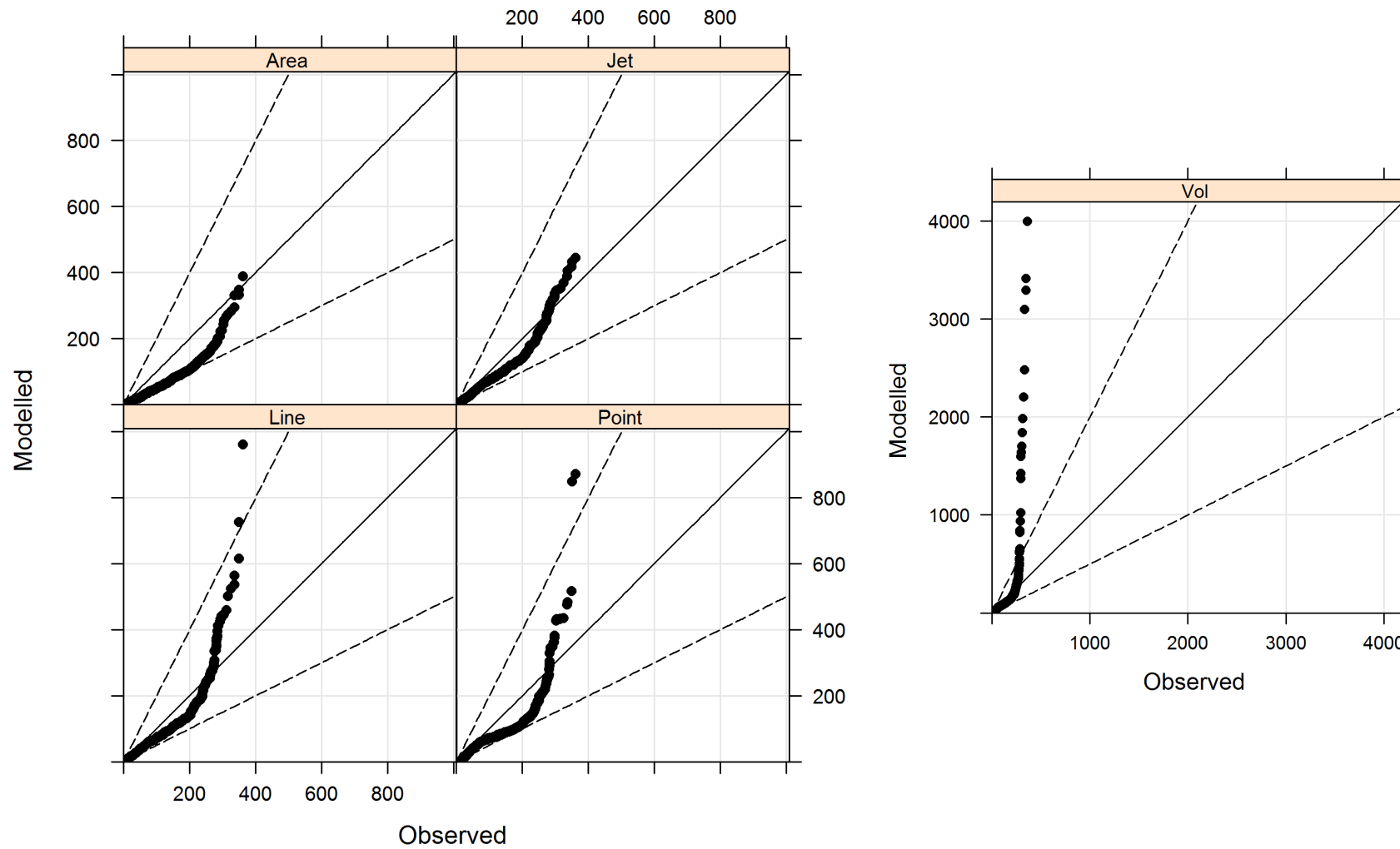


Figure 20 Quantile-quantile plots, comparing ADMS modelled against observed hourly average ammonia concentrations ($\mu\text{g}/\text{m}^3$) recorded at Whitelees farm for area, jet, line, point and volume sources; wind directions between 150° and 250° , observations $> 1 \mu\text{g}/\text{m}^3$; volume source results shown on different scale

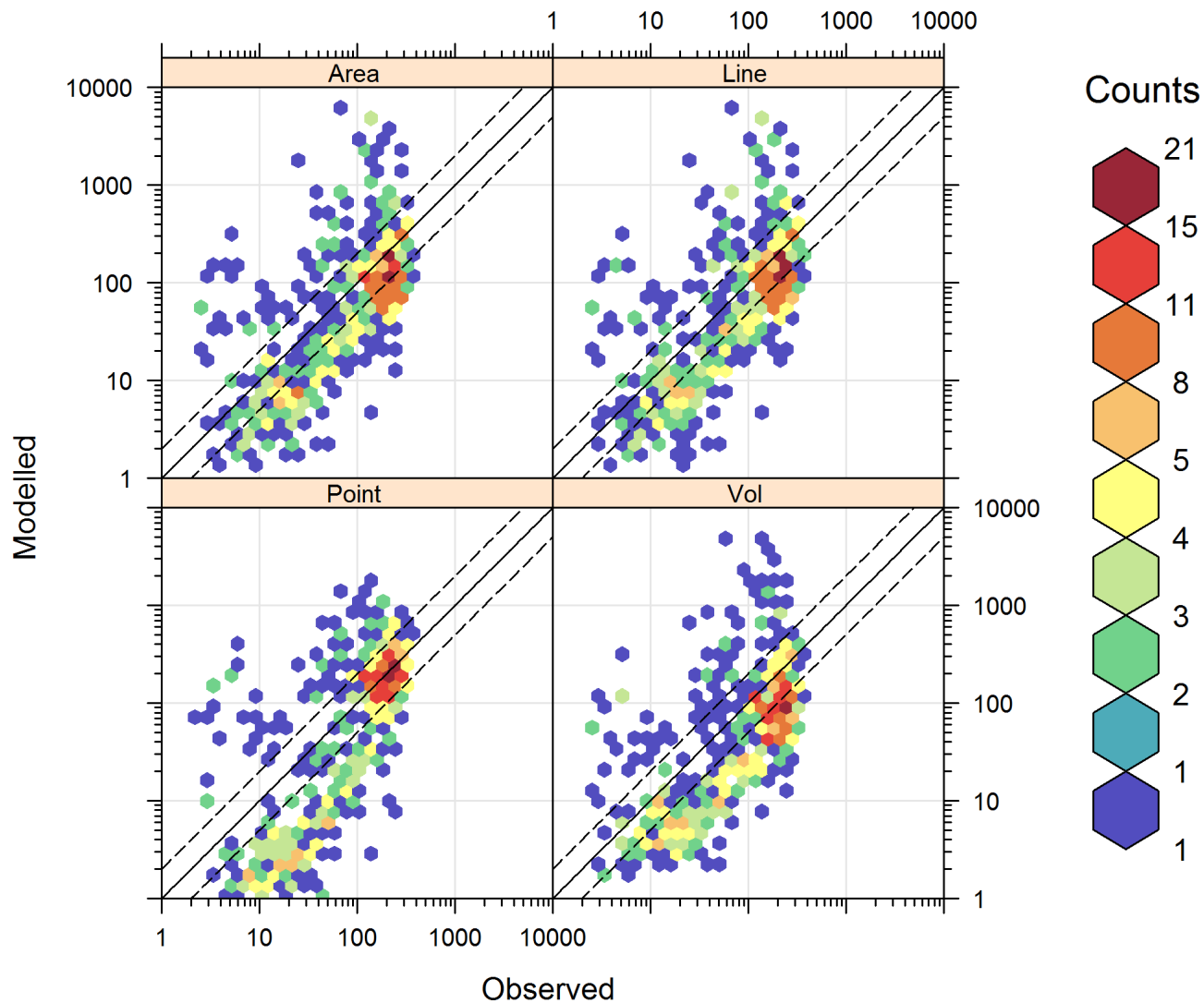


Figure 21 Frequency scatter plots, comparing AERMOD modelled against observed hourly average ammonia concentrations ($\mu\text{g}/\text{m}^3$) recorded at Whitelees farm for area, line, point and volume sources; wind directions between 150° and 250° , observations & modelled values $> 1 \mu\text{g}/\text{m}^3$

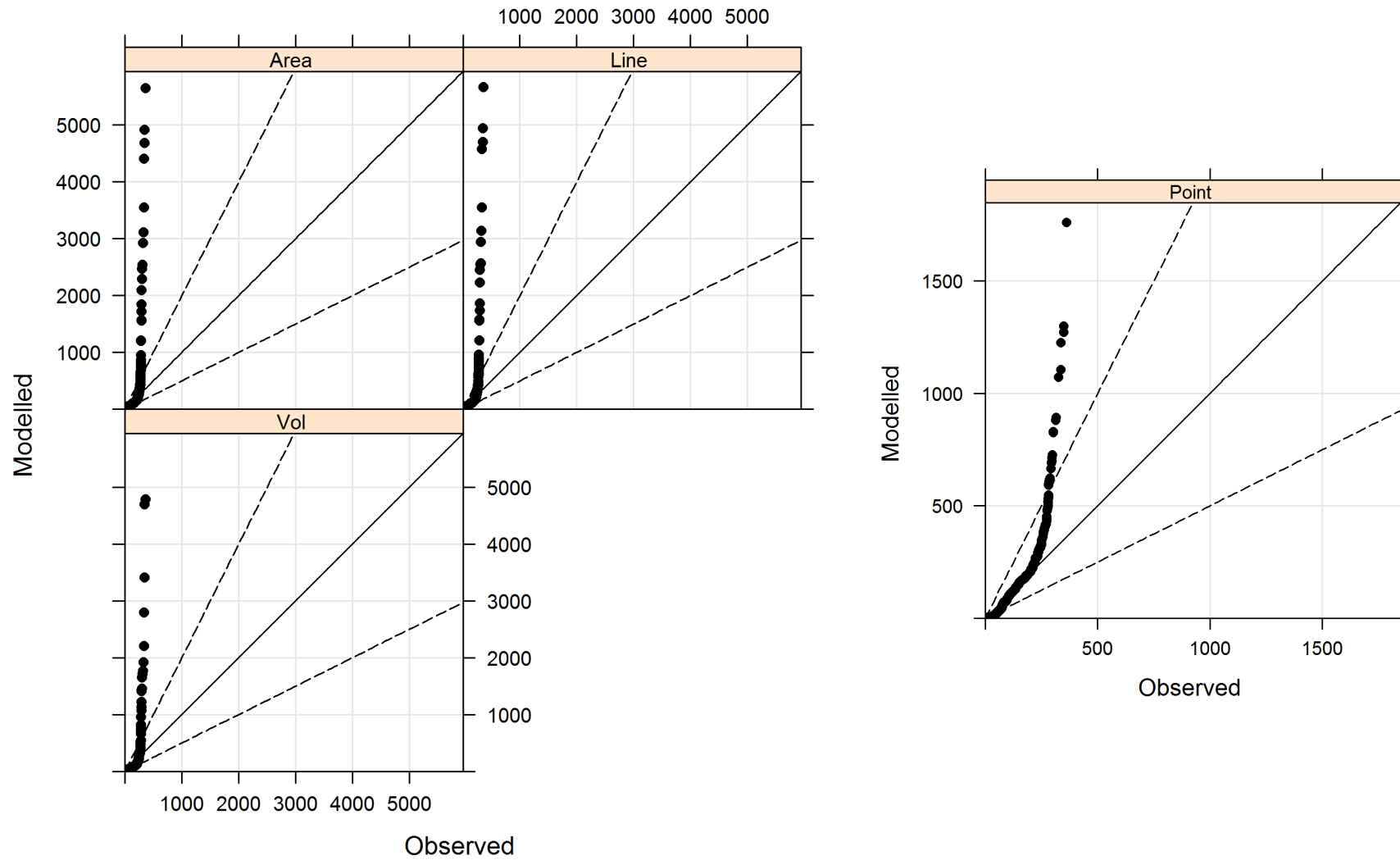


Figure 22 Quantile-quantile plots, comparing AERMOD modelled against observed hourly average ammonia concentrations ($\mu\text{g}/\text{m}^3$) recorded at Whitelees farm for area, line, point and volume sources; wind directions between 150° and 250° , observations $> 1 \mu\text{g}/\text{m}^3$; point sources shown on different scale

4.2.4.2 *Alpha sampler ammonia measurements*

Monitored time-integrated NH₃ concentrations were measured using Alpha samplers for 4 periods on an approximately monthly frequency, as described in Section 4.2.1. Meteorological data were only available for the periods covered by 'Run 2', 'Run 3' and 'Run 4'; therefore, 'Run 1' was not modelled. Further, there were no poultry in the sheds during 'Run 4', so this period was not modelled. Modelled average ammonia concentrations at the measurement locations are presented graphically in Figure 23.

These long-term ammonia measurements are useful because they provide information about the spatial distribution of pollutant concentrations. By comparing these measurements to contour plots of modelled data, it is possible to assess how well, on average, the models are predicting the spatial variation of concentrations. Figures 24, 25, 55, 56 and 57 present the 'Run 2' modelled results as contour plots, with the observation data overlaid.

4.2.4.3 *Short-term odour measurements*

Results for a single transect of odour measurements have been modelled in ADMS and AERMOD, using the same source configurations as for the ammonia continuous monitoring. In order to assess the uncertainty in model results relating to the variations in wind direction, results for a range of wind directions have been presented, that is:

- the observed wind direction, and
- the observed wind direction $\pm 15^\circ$.

The concentrations modelled at each receptor location for these three wind directions have been calculated and ordered in terms of the minimum, median and maximum values. Figure 26 shows the results, with the red line showing the observed odour concentrations, the full black line showing the median modelled concentrations and the dashed black lines showing how predictions may vary given uncertainty in the wind direction. The receptor numbers correspond to the values on Figure 18.

4.2.5 Discussion

The Whitelees dataset is very useful in assessing dispersion model performance relating to the modelling of agricultural sources. The emissions, meteorological measurements and concentration data selected for use (i.e. excluding the PM₁₀ data) are robust. It has been useful to have the three different measurement datasets to support any conclusions drawn.

Overall, it appears that the inclusion of the effects the initial momentum and, in cold conditions, also the buoyancy of the releases from the sheds are critical for realistic modelling. The model evaluation statistics for all the modelling cases where these effects are included show good performance; i.e. for ADMS releases as jet, point, line and area sources, for AERMOD when the release is modelled as a point source. Conversely, for the configurations where these effects are not included, model performance is much reduced. Overall the best agreement with measurements is achieved when a jet source is used in ADMS; this is reassuring

since this is the case which most accurately represents the release configuration. For the case of continuous ammonia measurements, the correlation coefficient is 0.63 and over 50% of values are within a factor of two of the observed and there is on average a small under prediction; the monthly measurements also agree well for 'Run 2' and 'Run 3', and the results of the odour modelling are reasonable. For AERMOD, a jet source was not appropriate because the source configuration in that model must be wind aligned. For the point source case in AERMOD, the only case where model performance is good, evaluation statistics are similar to those for ADMS with a correlation coefficient of 0.48 and over 40% of values are within a factor of two of the observed. As with ADMS, monthly measurements also agree well for 'Run 2' and 'Run 3', and the results of the odour modelling are good, showing less sensitivity to wind direction than ADMS, a result related to the models different treatment of building effects. However maximum concentrations from AERMOD show a much greater over prediction than those of ADMS.

Neglecting plume rise in ADMS (volume sources) and AERMOD (volume, line and area sources) results in over predictions of some measured concentrations. See for example the quantile-quantile plots for the continuous monitoring shown in Figures 20 and 22, and the 'Run 2' monthly results. ADMS also appears to over predict the odour measurements for the first third of the points on the transect; AERMOD gives a better result for that case – the difference between the models is likely to be related to the shorter averaging time used in ADMS for the odour modelling.

The idealised modelling described in Section 3 the conclusions drawn from this model evaluation exercise. Specifically, Figure 9 a) indicates that the volume source concentrations are similar to the area and line source concentrations by 100 m downwind of the source (apart from low level line and area source in AERMOD), independent of source height. Conversely, when plume rise is modelled, the concentrations at this distance are much reduced. This supports the argument that it is the lack of plume rise, rather than the source configuration, that is causing the over prediction of concentrations for the non-buoyant sources in this Whitelees model evaluation study.

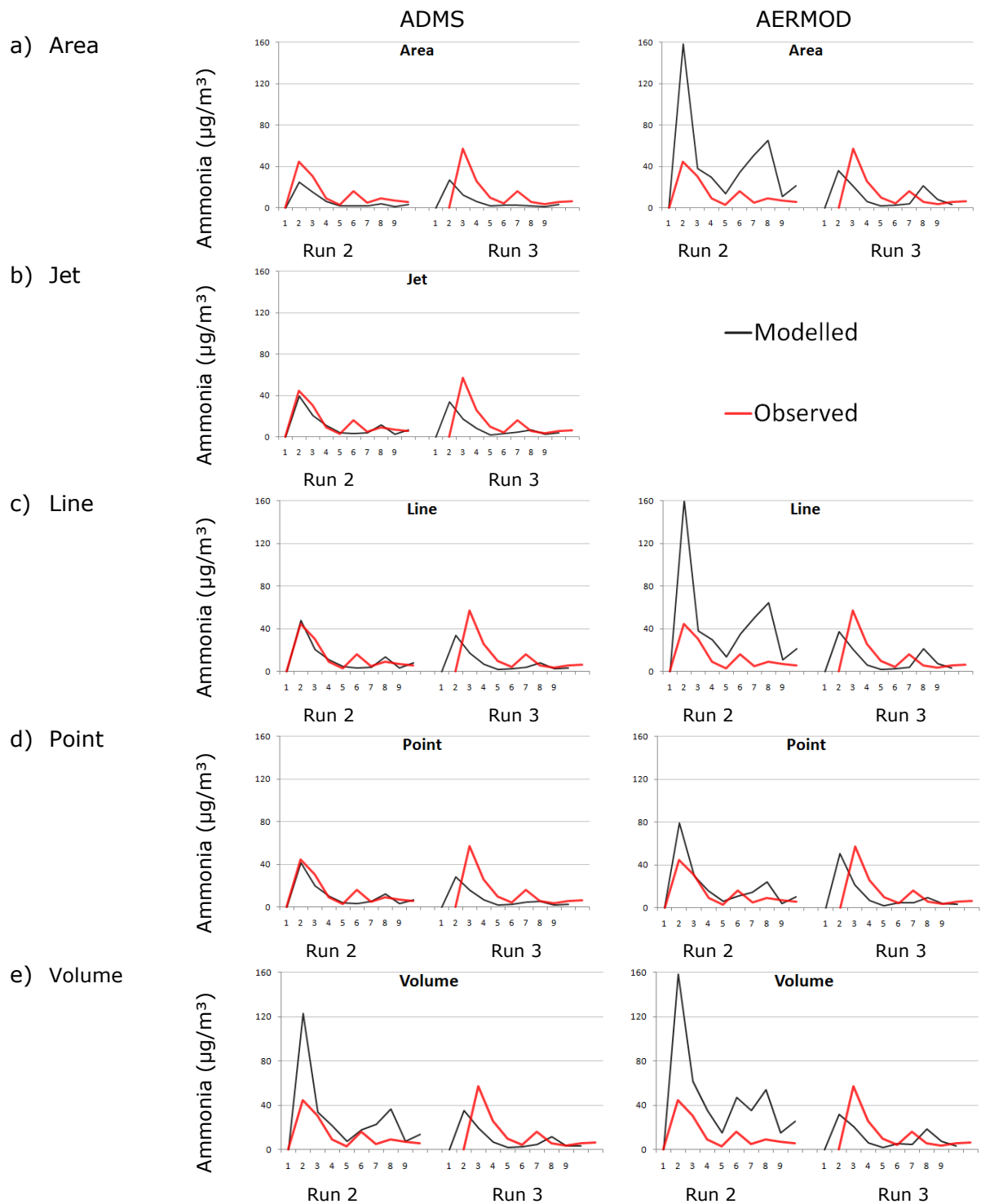


Figure 23 Period average ADMS and AERMOD ammonia results for Whitelees ('Run 2' and 'Run 3') when modelling using a) area, b) jet, c) line, d) point and e) volume sources; observations shown in red, median modelled values shown in black, all plots use same scale.

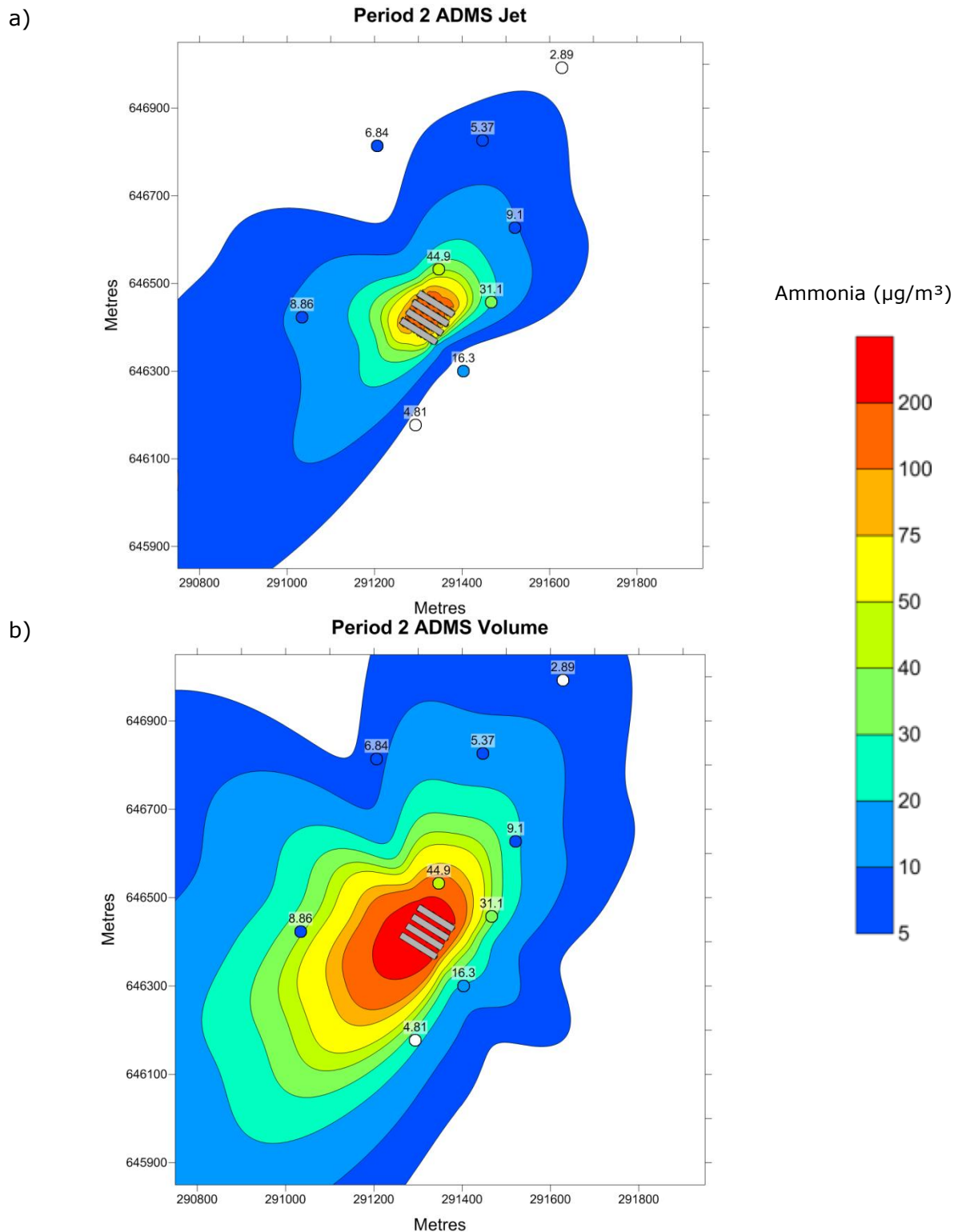
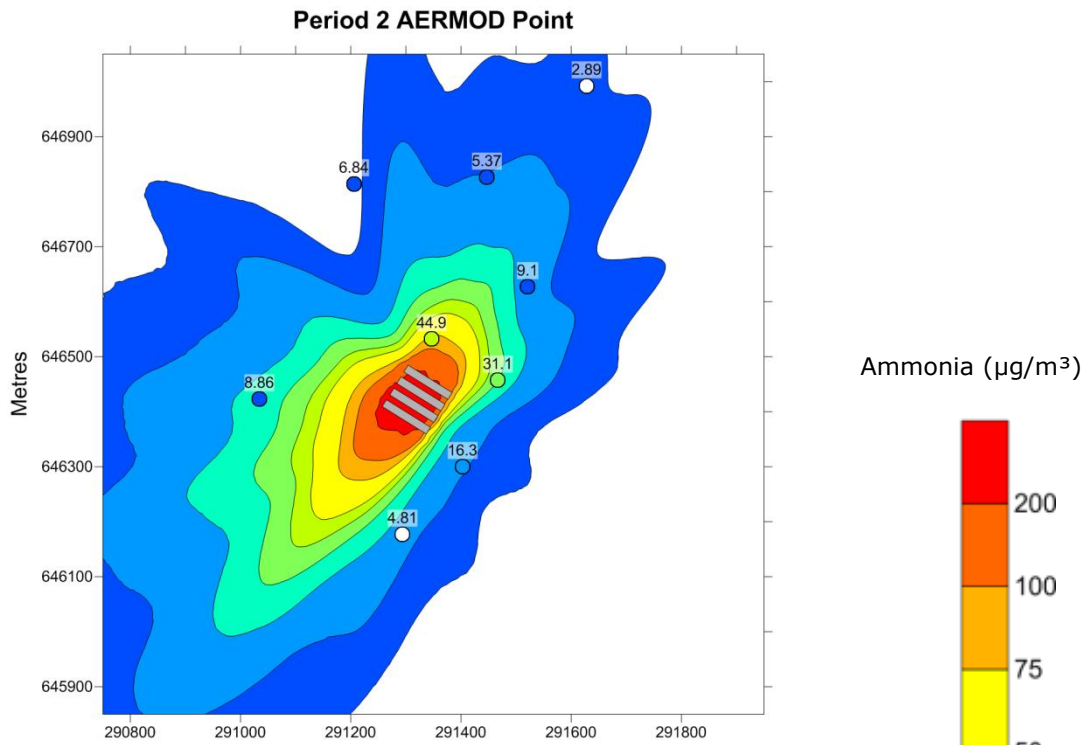


Figure 24 Period ADMS ammonia results for Whitelees for 'Run 2' when modelling using a) jet and b) volume sources. Observations shown by the circles, model results shown by the contour; all plots use same colour scale and the buildings are shown in grey (not modelled explicitly).

a)



b)

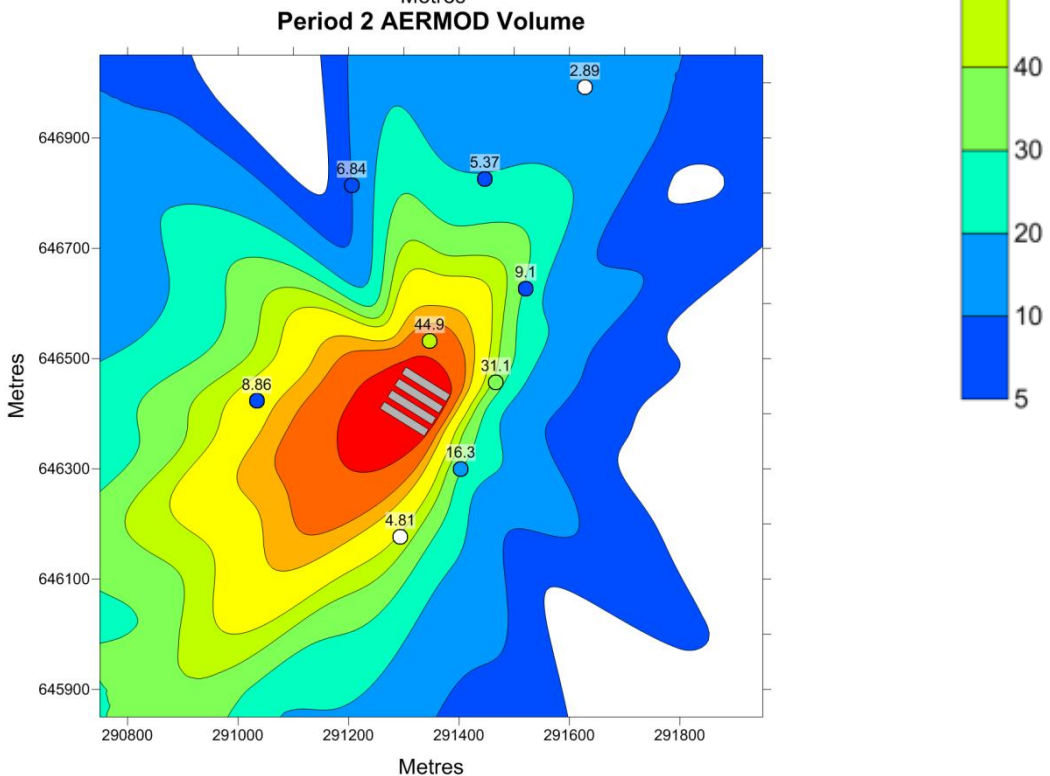


Figure 25 Period AERMOD ammonia results for Whitelees for 'Run 2' when modelling using a) point and b) volume sources. Observations shown by the circles, model results shown by the contour; all plots use same colour scale and the buildings are shown in grey (modelled explicitly for point source run, but not for volume source run).

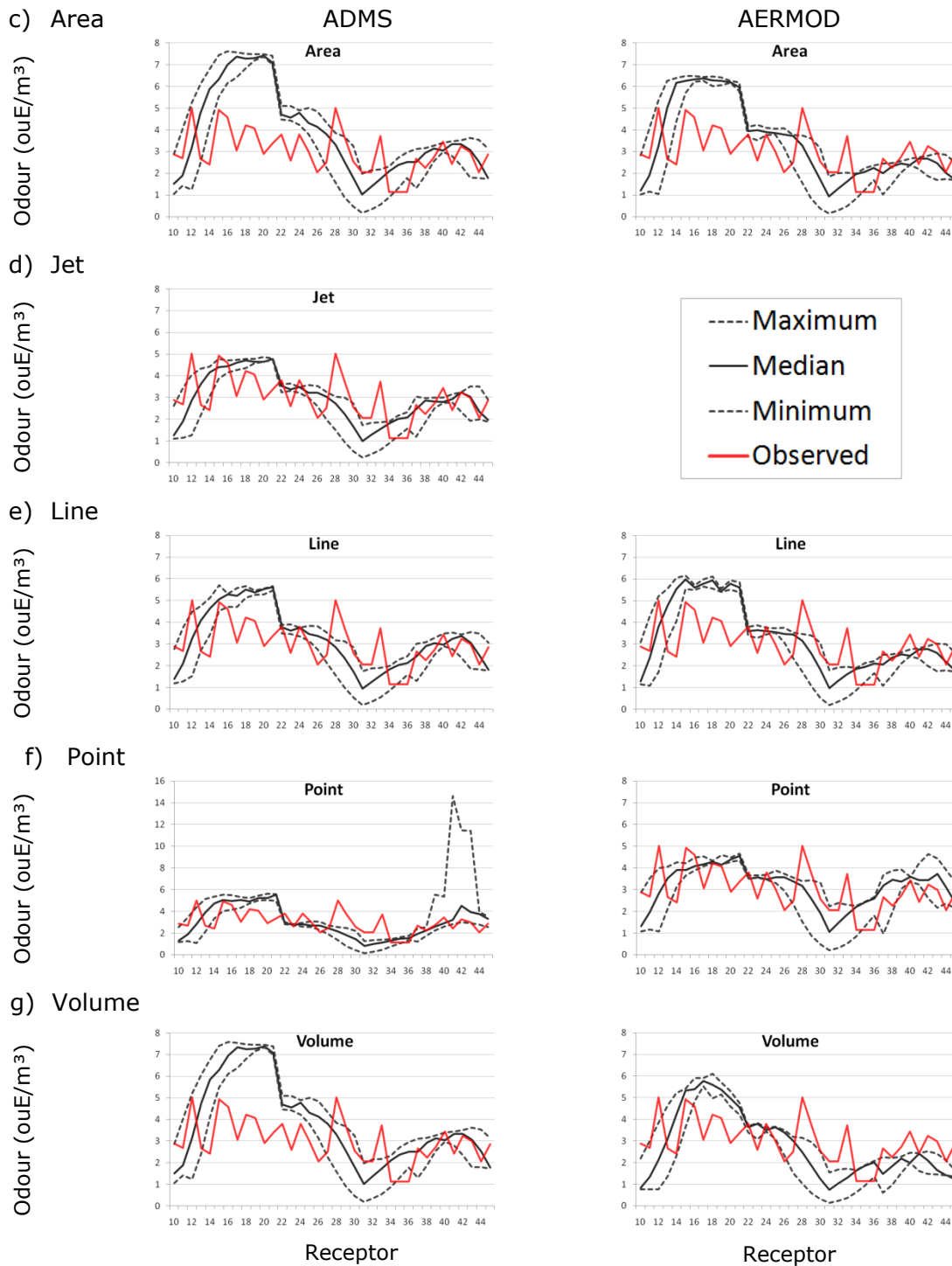


Figure 26 Short-term ADMS and AERMOD odour results for Whitelees when modelling using a) area, b) jet, c) line, d) point and e) volume sources; observations shown in red, minimum, median and maximum modelled values shown in black, where range of modelled values corresponds to wind direction adjustments of $\pm 15^\circ$; all plots use same scale apart from the ADMS point source results, which use a larger scale due to the range of modelled values for this source type.

4.3 Farm F (Defra poultry dataset)

4.3.1 Site configuration and emissions

180 000 broilers are housed in six sheds on this farm. Approximately two thirds of the birds are housed in sheds that are ventilated using an 'End Ventilation System'; that is, the majority of the emissions from these sheds are released from one end. The remaining birds are housed in three sheds that use ridge mounted fans.

The emission concentration and ventilation rates used for this study are given in Table 35. The PM₁₀ emission concentrations are the measured fan exit concentration values, but the ventilation rate is a 'winter' estimate for the entire farm. The calculated emission rate is also given. The emissions are split into 'light' and 'dark' periods which correspond to when the lights are on in the shed (and hence there is more activity, and higher emissions).

Table 35 Farm F emission and ventilation rates

Period	Emission concentration (µg/m ³)	Ventilation rate (m ³ /s)	Emission rate (µg/s)
Light 1	1164		77394
Dark 1	547	66.5	36370
Light 2	1173		77992
Dark 2	690		45878

Ventilation rates in the shed were measured directly during the campaign using the tracer gas SF₆. However, the reported rates appear very high compared to what would seem necessary for sheds of this size at this time of year, and seem inconsistent with the capacity of the two fans which are stated as operating most of the time. Therefore, industry standard ventilation rates were used in the modelling, which are consistent with the capacity of the two fans that were stated as operating.

The suggested dust emission rate for broilers is 0.1 kg dust/animal/year (EA, 2013) and the general rule of thumb is to assume that PM₁₀ is approximately 20% of dust emissions i.e. 0.02 kg PM₁₀/animal/year. The measurements at Farm F result in a PM₁₀ emission rate of 0.013 kg PM₁₀/animal/year, which is less than, but reasonably close to, the EA value. The discrepancy between the recommended and measured values for this study is likely to be related to the assumption that PM₁₀ is 20% of dust emissions, in addition to: variations in emissions due to the stage in the cycle; inaccuracies in the measured fan exit concentrations; and the assumptions relating to the estimation of the ventilation rates.

Performing buoyancy and momentum flux calculations in line with the methodology given in the ISC3 document (APPENDIX E) indicates that buoyancy dominates plume rise; this is unsurprising as the fans are vertically mounted, resulting in a horizontal momentum flux.

4.3.2 Measurements

During the winter campaign at Farm F, PM₁₀ measurements were taken upwind of the farm buildings, and then at different distances downwind, up to 400 m. Figure 27 shows the observation data against distance downwind. Measurements were recorded during two light periods (1700 – 1200) and two dark periods (1300 – 1600) although observations have not been reported at all locations for all periods, presumably due to robustness of the values recorded.

It has not been possible to obtain detailed information relating to the times of the measurements and their locations; it is unlikely that the measurements are an average over the full period, so this information would be very useful for model evaluation. As the location of the measurements is unknown, it is difficult to know precisely the definition of 'downwind'; it has been assumed that the distance given is relative to the exit fan where the measurements were taken. The consequence of the measurement uncertainty is that this dataset cannot be considered robust in terms of dispersion model evaluation.

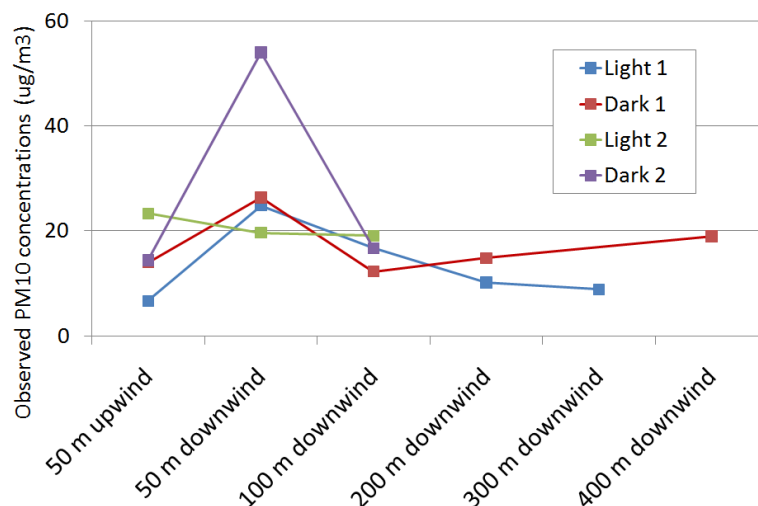


Figure 27 Winter observations from Farm F (Defra poultry dataset)

During the 'Light 2' period, the 'downwind' observed concentrations were lower than the upwind values, indicating that the recorded measurements may not have been in the correct location with respect to the prevailing wind direction; an upwind trend in observed concentrations is also seen during the Dark 1 period for the 200 and 400 m measured values. In addition, as these measurements are recorded in the vicinity of buildings, it may be that complex flow fields lead to a non-monotonically decreasing relationship between pollutant concentrations and distance 'downwind'.

Figure 28 shows the fan configuration at the end of the three sheds of interest at Farm F. The upper fans are in use during the winter campaign; the lower fans are used for additional ventilation during hot weather. Measurements of fan exit concentration rates were recorded during each light and dark period, as were emissions within the shed. The fan exit concentrations, together with an

estimate of the ventilation rate for the farm, were used to calculate the source emission used in the modelling.

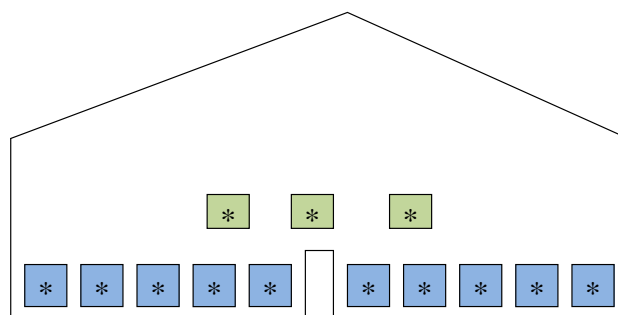


Figure 28 Approximate location of the fans on the end of the Farm F sheds indicated by '*'; green rectangles show the location of the fans in use during the winter campaign; blue squares show additional fan locations for summer ventilation (figure edited from documentation provided by Theo Demmers)

4.3.3 Model set up

4.3.3.1 Source configurations and efflux parameters

Figure 29 shows the horizontal representation of each source type (point, jet, line and volume) used to model the release and Table 36 summarises the source parameters used. For this study, the roof vents on the three smaller sheds (shown in Figure 29 and referred to as 'Point (top)' in Table 36) were modelled as point sources for all model configurations; these were not the focus of the measurement campaign, and consequently have not been considered in detail. The tunnel vents at the ends of the three larger sheds have been modelled as points, jets, volume and line sources at heights of approximately 3 m, as this is the location of the upper vents shown in Figure 28. An area source was considered inappropriate for this source type, as the emissions from the sheds are released from a relatively small region and the ventilation system ensures that emissions do not leak from other parts of the shed. As the release is horizontal, the jet source has been configured to approximately represent the fan vent; as the release is not vertical, the point and line sources have a very small exit velocity; this has been set sufficiently high (0.1 m/s) to allow the modelling of plume rise in ADMS.

The value of surface roughness has been taken as 0.2 m. As for Whitelees, ideally, sensitivity analyses assessing the dependence of model results on the value of roughness length would be performed, but it was not possible to do such analyses due to project constraints.

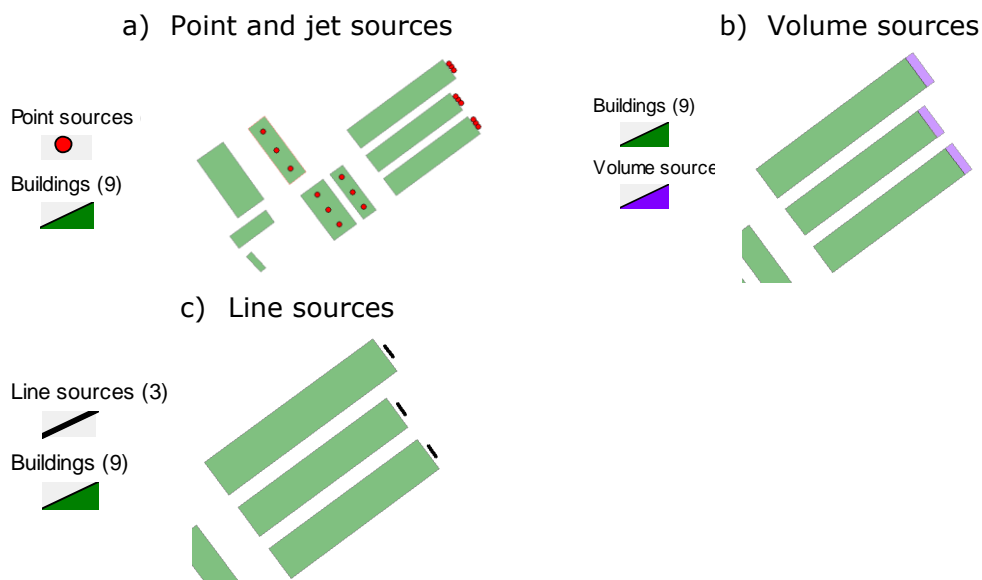


Figure 29 Horizontal source representations for Farm F (Defra poultry dataset); buildings explicitly modelled with point sources only

Table 36 Farm F source parameter ranges *ADMS only, AERMOD jet sources are wind aligned

Idealised source type	Source dimensions (m)			Efflux parameters	
	Height (m)	Dimensions: Length (m) x Width (m) (x depth, m)	Elevation angle to horizontal*	Temperature (°C)	Velocity (m/s)
Point (top)	5.25	n/a	n/a	22	0.1
	5.75			22	11
Point (end)	3	n/a	n/a	22	0.1
Jet	3	n/a	0°	22	10
Volume	2.5	18 x 5 (x 1)	n/a	n/a	n/a
		20 x 5 (x 1)			
Line	3	7.5 x 1	n/a	22	0.1

4.3.3.1 Meteorological data

Onsite wind speed and wind direction measurements were taken. These data were supplemented with cloud cover information from a local UK Met Office weather station.

4.3.3.2 Output locations and settings

As the exact location of the measurements is not known, the approach of defining a receptor arc at the downstream distances of interest has been taken.

Figure 24 shows the source and receptor configuration. Receptors were located at 1.5 m above ground level.

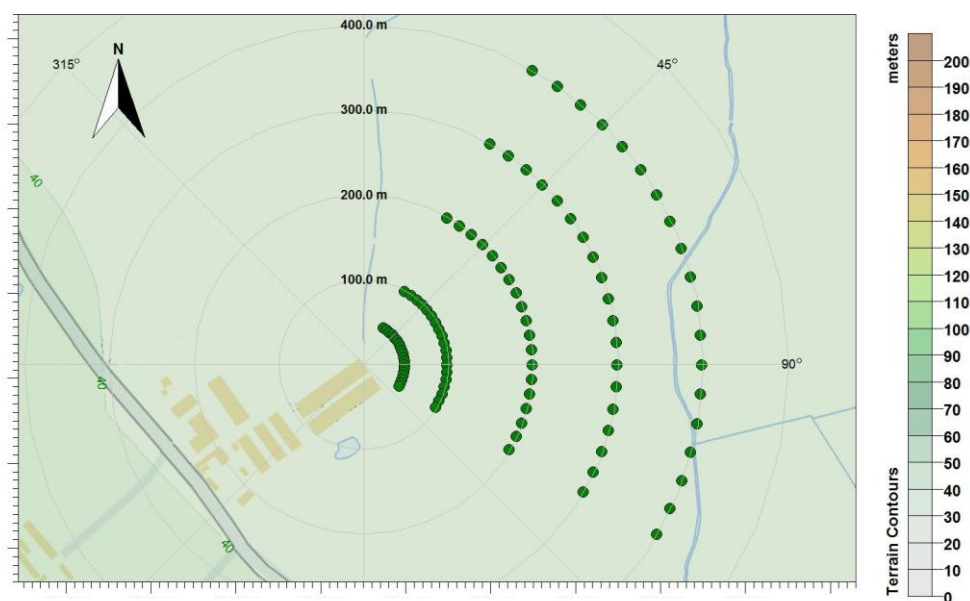


Figure 30 Study set up for Farm F showing buildings (brown rectangles) and receptor arcs (dark green dots); background map courtesy of © Crown copyright and database rights, 2015.

4.3.4 Results

Figure 31 compares the observed and modelled results for each of the two light and dark periods at the different distances downwind of the sheds. Wind roses giving the wind speed and direction for each of the periods are also shown. Here, the maximum concentration over the receptor arc has been taken as the modelled concentration for any particular hour. Then, for each light and dark period, the minimum, average and maximum of these hourly arc-max concentrations have been calculated. As only downwind concentrations have been modelled, and modelled without the inclusion of a background, the observed concentrations have been presented relative to the upwind value. This subtraction of upwind concentrations has resulted in some observations that are negative, for example during the second light period, where the 'downwind' concentrations were lower than the upwind values. By analysing the arc-max concentrations in this way, the analysis assumes that the observation represents the maximum concentration within the plume. As no information regarding the time or location of the measurements is available, it is difficult to assess whether or not this approach is robust.

4.3.5 Discussion

As the 'Light' and 'Dark' periods for Farm F do not correspond to day and night, it is not possible to draw conclusions relating to the dependence of the models on meteorology for this dataset. However, as the 'Dark' periods are only four hours, the variation in meteorology and model results are limited compared to the 'Light' periods. It may be that during the 'Light' period, observations are underestimated because there are more instances of the monitors not coinciding

with the downwind plume. Consequently, the 'Dark' measurements are likely to constitute a more robust dataset for comparison purposes.

In terms of the observations, the largest recorded value is the 50 m downwind value for the Dark 2 period, where the PM_{10} increment is close to $40 \mu\text{g}/\text{m}^3$. Both ADMS and AERMOD give a reasonable prediction for this value for the majority of source types, although the ADMS jet source and the AERMOD line source have a tendency to predict values lower than the observations. Looking at the measured decay for this observation period, which is a very large drop of 38 to $2 \mu\text{g}/\text{m}^3$, ADMS models this best using the jet and point source (with building) configurations; AERMOD concentrations are reasonably similar, slightly over predicting, for all source types at the 100 m distance.

Measurements were recorded up to 300 m for the Light 1 period. Here, both models generally predict concentrations greater than the measured values, although this inconsistency between modelled results and observations may be due to an underestimate in the latter dataset. ADMS agrees reasonably well with the measured concentrations and the downwind decay when a jet source is used; AERMOD's best prediction at the 50 m distance is the point source (with building), but the modelled downwind decay is not sufficiently large.

The Dark 1 measurements are not very robust: the 100 m increment is negative, and the 400 m increment is over four times larger than the value recorded at 200 m. The models' inability to predict the 100 m measurement is likely to be due to the monitor not being located correctly downwind for this measurement period. The high measurement at 400 m may be related to other sources of PM_{10} in the vicinity of the monitor, complex plume fluctuations (possibly related to the presence of the buildings) or an error in the measurement analysis. For the more robust 50 and 200 m measurements for this period, all model predictions at 50 m are reasonably accurate, but neither ADMS nor AERMOD models the full decay at 200 m.

Both the 50 and 100 m increments for the Light 2 period are negative, indicating that the monitor missed the plume for this time period; further the modelled receptor arc could be considered insufficient when considering the wind directions recorded during this period. Interestingly, both models predict a relatively high concentration when the volume source representation is used, much higher than during any of the other periods. Similarly to the volume sources, the point source (with building) in ADMS and the line and point sources (no building) in AERMOD also have relatively high concentrations. This may be a time period when the initial momentum and buoyancy of the plume is important, and the modelling of the ADMS and AERMOD volume sources and the AERMOD line source leads to unphysically high modelled concentrations at the receptor height.

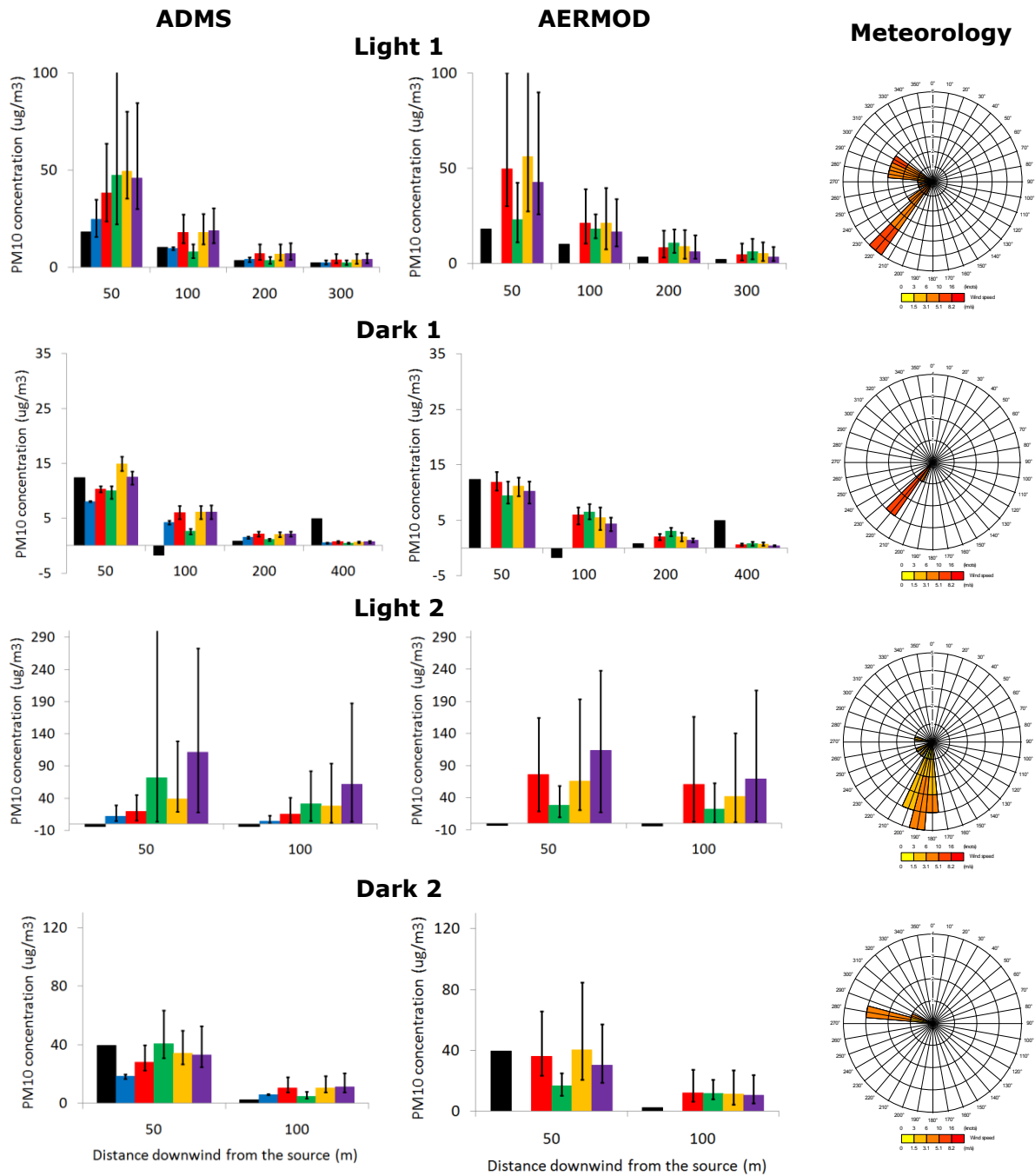


Figure 31 Farm F (Defra poultry study) monitored increments (relative to upwind) and modelled results for all periods for ADMS (left) and AERMOD (right); bar chart shows average concentrations over the full period; error bars show maximum and minimum concentrations; scales vary with period, and not all of the maximum values are shown.

Given the uncertainty regarding the time and location of the measurements, the models are representing the observations reasonably well in most cases. However, it is not possible to highlight a particular non-point source type that is significantly better than another from this study. The jet sources modelled in ADMS predict lower concentrations in general, which is related to the relatively high exit velocity modelled in this case. Also, when a point source is modelled with a building, the concentrations predicted by AERMOD tend to be lower and have less variation than those predicted by ADMS.

If these measurements are considered robust, a general conclusion from this study is that neither ADMS nor AERMOD represent the *full* decay downwind. However, the non-point sources appear to give a more reliable prediction of the decay than when a point source is modelled with a building. For example, Figure 32 shows the 'Light 1' ADMS and AERMOD modelled decay at downwind distances of 100, 200 and 300 m normalised by the 50 m concentration, compared to the observed concentrations at the same distances, normalised by the observed concentrations. Here, the ADMS and AERMOD modelled decay for the non-point sources, and point source modelled without a building compare reasonably well to the observed; when a building is modelled, ADMS under predicts and AERMOD over predicts the decay. This particular example suggests that the non-point sources may give a more reliable dispersion decay downwind of the source.

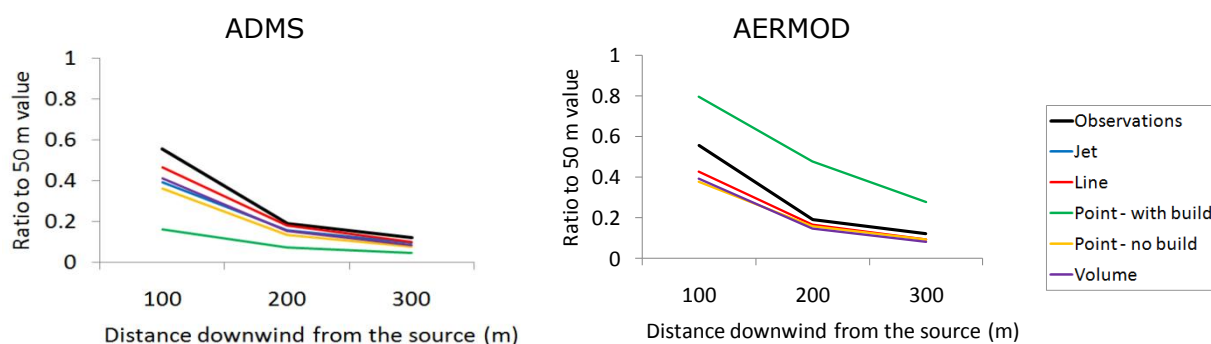


Figure 32 Concentration decay for the 'Light 1' period, shown relative to the 50 m concentration measurement for ADMS (left) and AERMOD (right)

4.4 Farm G (Defra poultry dataset)

4.4.1 Site configuration and emissions

Nearly 200 000 broilers are housed in six virtually identical and aligned sheds on this farm. These sheds are ventilated using an 'End Ventilation System', as for Farm F, but the sheds use an emissions abatement system where the air leaving the sheds passes through a baffle. Figure 33 shows schematically how the baffle slows down the flow of air, resulting in accelerated deposition of particles (compared to the situation when no baffle is present) and also a vertical rather than horizontal release.

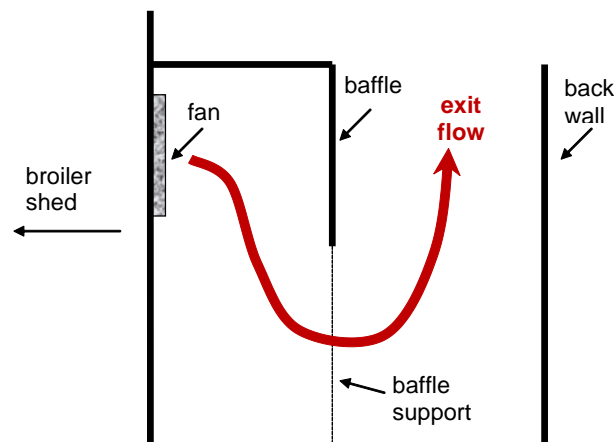


Figure 33 Schematic showing baffle, which is used for emissions abatement at Farm G (figure edited from documentation provided by Theo Demmers)

Measurements of pre- and post-abatement fan exit concentrations were recorded during each 'light' and 'dark' period, as were emissions within the shed. The measurements of exit concentrations as they were released after passing through the baffle were used together with measured fan ventilation rates to calculate the source emission used in the modelling, as these were considered more robust than the measured emissions within the shed.

The emission concentration and ventilation rates used are given in Table 37. The ventilation rate is time-varying so for brevity the average ventilation rate for each period is given in the table. A typical calculated emission rate is also given in the table, based on the average ventilation rate. Note that, in the modelling, the precise time-varying value was used i.e. the values given in the table are therefore just indicative. As for farm F, the emissions are split in to light periods and dark periods which correspond to when the lights are on in the chicken sheds (and hence there is more activity).

The measurements at Farm G result in a PM_{10} emission rate of 0.017 kg PM_{10} /animal/year, a value quite close to 20% of the suggested dust emission rate value, 0.1 kg dust/animal/year (EA, 2013).

Performing buoyancy and momentum flux calculations in line with the methodology given in the ISC3 document (APPENDIX E) indicates that buoyancy dominates the plume rise.

Table 37 Farm G emission and ventilation rates

Period	Emission concentration ($\mu\text{g}/\text{m}^3$)	Average ventilation rate (m^3/s)	Typical emission rate ($\mu\text{g}/\text{s}$)
Light 1	1091	182	198562
Dark 1	432	151	65232
Light 2	862	181	156022
Dark 2	394	134	52796
Light 3	867	168	145656

4.4.2 Measurements

During the winter campaign at Farm G, PM_{10} measurements were taken upwind of the farm buildings, and then at 50 and 100 m downwind. Measurements were taken during three light periods (0500 – 2300) and two dark periods (0000 – 0400). As for Farm F, it has not been possible to obtain detailed information relating to the times of the measurements and their locations; consequently this dataset cannot be considered robust in terms of dispersion model evaluation. Figure 34 shows the measurements that are available for model evaluation purposes.

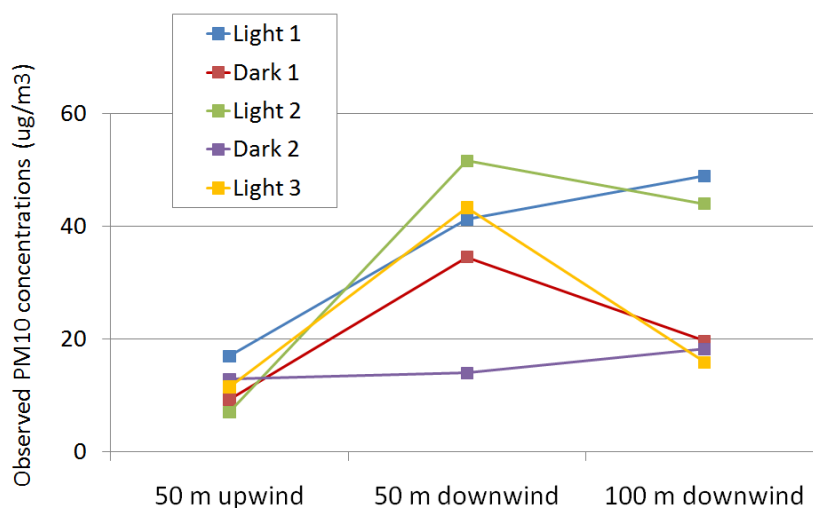


Figure 34 Winter observations from Farm G (Defra poultry dataset)

As for Farm F, there are possible issues with this dataset. During the 'Light 1' and 'Dark 2' periods, an upward trend in observed concentrations is seen between the 50 and 100 m measured values; this may however be related to flow recirculation downwind of the building, where the concentrations in the immediate vicinity of the building are lower than those in the mid-field, where the plume has been grounded.

4.4.3 Model set up

4.4.3.1 Source configurations and efflux parameters

Figure 35 shows the horizontal representation of each source type (point, volume, area and line) used to model the release. In contrast to Farm F, it is now appropriate to consider the emissions as an area source, as the baffle release is vertical; it is no longer necessary to consider a jet source for the same reason. Table 36 summarises the source parameters used.

The value of surface roughness has been taken as 0.3 m.

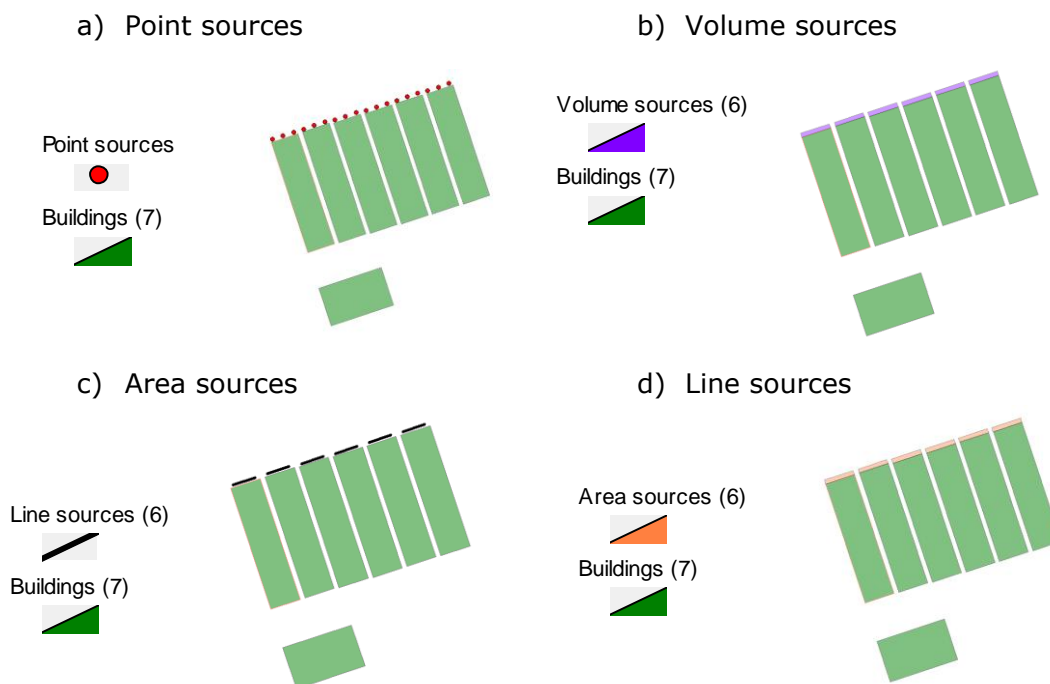


Figure 35 Horizontal source representations for Farm G (Defra poultry dataset); buildings explicitly modelled with point sources only

Table 38 Farm G source parameter ranges

Idealised source type	Source dimensions (m)		Efflux parameters	
	Height (m)	Dimensions: Length (m) x Width (m) (x depth, m)	Temperature (°C)	Velocity (m/s)
Point	4	n/a	22	0.25
Volume	4	21 x 3 (x 2)	n/a	n/a
Area	4	21 x 3	22	0.25
Line	4	17 x 1	22	0.25

4.4.3.1 Meteorological data

Onsite wind speed and wind direction measurements were taken. These data were supplemented with cloud cover information from a local UK Met Office weather station.

4.4.3.1 Output locations and settings

As for Farm F, the approach of defining a receptor arc at the downstream distances of interest has been taken. Figure 36 shows the source and receptor configuration. Due to lack of information relating to the exact location of where the measurements were taken, the arc has been defined relative to the ends of the sheds where the fans are located; clearly the lack of information relating to measurement locations adds uncertainty to the modelling. Receptors were located at 1.5 m above ground level.

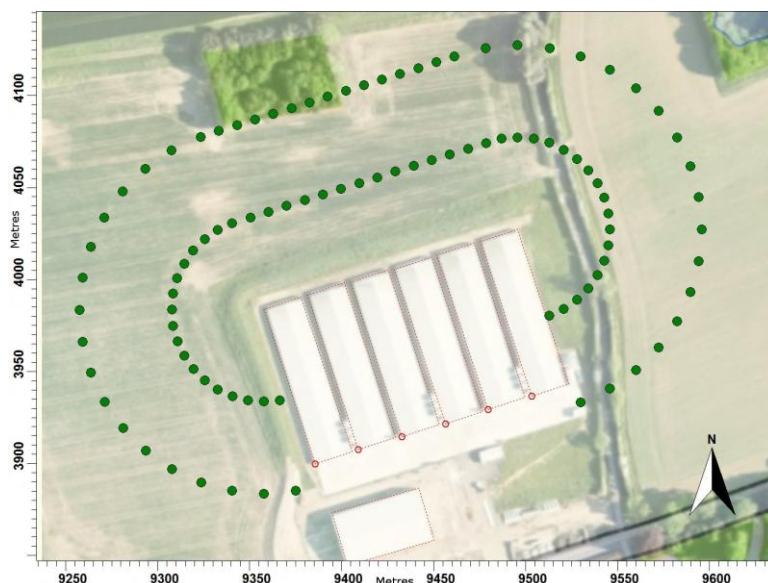


Figure 36 Study set up for Farm G showing buildings and receptors (dark green dots); background map courtesy of © Crown copyright and database rights, 2015.

4.4.4 Results

Figure 37 compares the observed and modelled results for the three light and two dark periods at the different distances downwind of the sheds. As for the Farm F comparisons, the maximum concentration over the receptor arc has been taken as the modelled concentration for any particular hour; it should be noted however, that there is more uncertainty regarding the modelled downwind distances for Farm G than for Farm F (compare Figures 30 and 36). For each light and dark period, the minimum, average and maximum of these hourly arc-max concentrations have been calculated. Only downwind concentrations have been modelled, and the observed concentration presented is relative to the upwind value.

By analysing the arc-max concentrations in this way, the analysis assumes that the observation represents the maximum concentration within the plume. As no information regarding the time or location of the measurements is available, it is difficult to assess whether or not this approach is robust.

4.4.5 Discussion

Although the 'Light' and 'Dark' periods for Farm G do not correspond to day and night, the 'Dark' period is solely during the night (midnight to 0400), so it may

be possible to reach some conclusions regarding model behaviour in stable meteorological conditions from inspection of these results. The 'Light' periods encompass a wider range of meteorological conditions.

In terms of the observations, both models give reasonably good predictions for the 'Dark 1 period', with ADMS having a slight tendency to predict values lower than observations, and AERMOD predicting slightly higher values. Of note is that the line source configuration in ADMS predicts concentrations that are too low in the near field, and the AERMOD set up incorporating point sources with buildings predicts values that are too high.

The 'Dark 2' period incremental observations increase with distance from the source, although measured values are small, indicating that the measurements may not have been taken within the plume, or because the plume was elevated due to slight buoyancy during the stable, night time conditions; the measurement issues may be due to the varied wind directions during this period. It is possible that the presence of the buildings causes the plume to ground some way from the source, resulting in higher concentrations in the mid-field compared to the near-field. AERMOD does predict an increase in concentrations with distance for the area, line and point source configurations, but the modelled concentrations far exceed the values observed. ADMS predicts much higher concentrations than observed for the volume source only, indicating that modelling the buoyancy of the plume reduces the ground level concentrations for this case.

Observed concentrations also increase with distance from the source for the 'Light 1' case, although the meteorology during this period appears more consistent so this increase may be valid, and again related to the presence of the buildings. Neither model captures the increase in concentration, and both have a tendency to over predict the concentrations at 50 m for all source types, with the 'point source with building' leading to the highest, and most varied predictions in concentrations during this period for both models.

Conversely, for the 'Light 2' period, the models demonstrate rather different performance, in particular for the line and area sources, where the ADMS predictions are much lower than the AERMOD values, due to buoyancy of the plume being modelled in ADMS. For ADMS, the volume source values are many times higher than the majority of other source configurations because buoyancy is not modelled. For AERMOD, the best model performance is for point sources, which supports the conclusion that buoyancy effects are important for this period.

The modelled results for the 'Light 3' period follow the same pattern as for the 'Light 2' period, although the measured concentrations are lower.

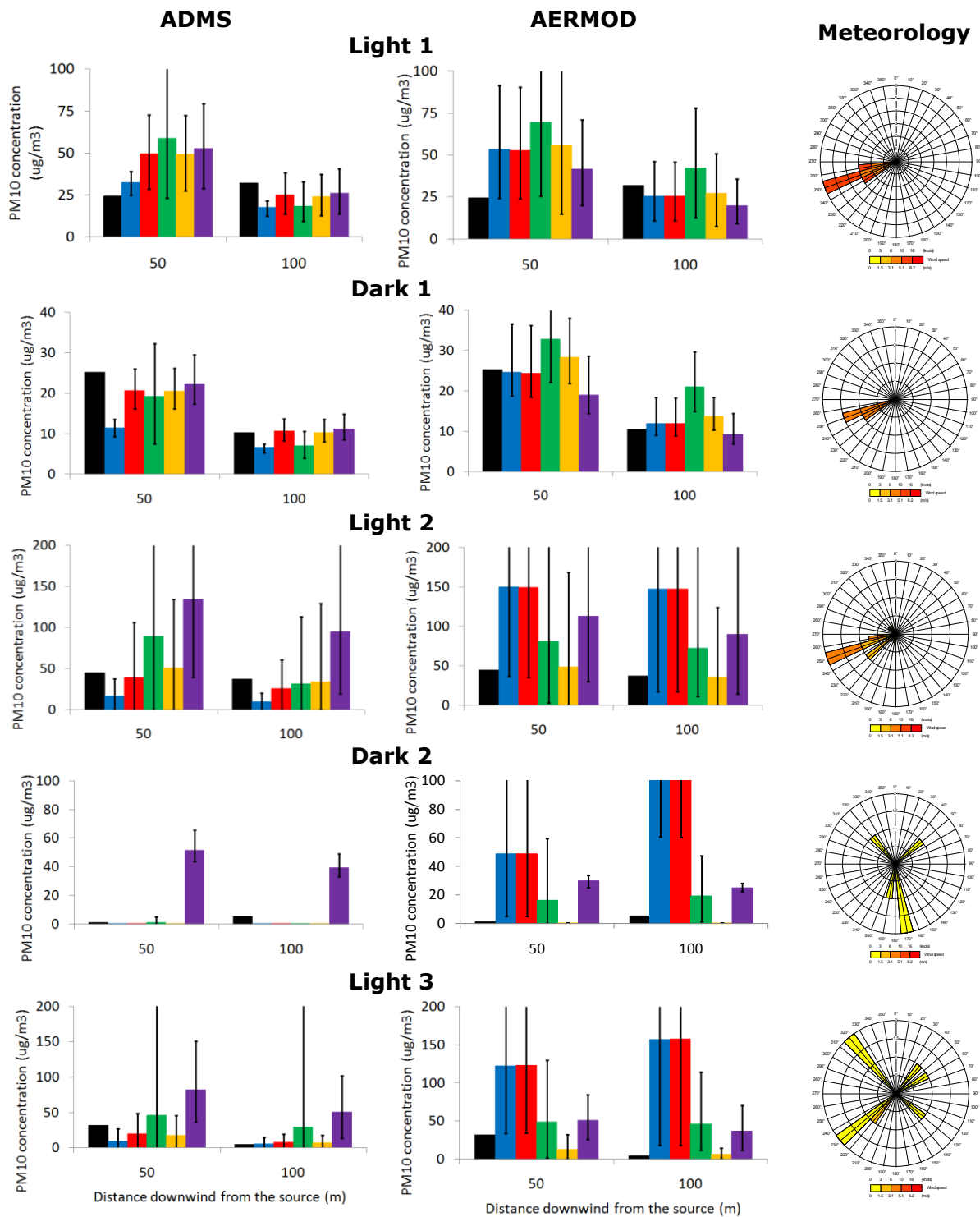
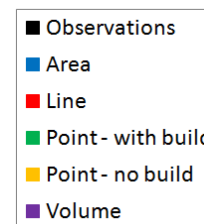


Figure 37 Farm G (Defra poultry study) monitored and modelled results for all periods for ADMS (left) and AERMOD (right); bar chart shows average concentrations over the full period; error bars show maximum and minimum concentrations; scales vary with period, and not all of the maximum values are shown.



4.5 Defra bioaerosol dataset

4.5.1 Site configuration and emissions

Although aerial photography was provided for the site, the locations of the windrows change with time. Further, no scale was provided relating to the aerial image. Therefore, for the modelling, the size of the windrow was approximated. The receptor locations are given as downwind distances from the source, but it is not known what constitutes 'downwind'. Consequently, this dataset cannot be considered robust in terms of dispersion model evaluation.

Due to the lack of robust emission measurements associated with the source, no attempt was made to model absolute concentrations at this site. Instead, the modelled concentrations were normalised to agree with the measurements for the highest measurement recorded downwind of the source; this was the value recorded at the first or second receptor.

Performing buoyancy and momentum flux calculations in line with the methodology given in the ISC3 document (APPENDIX E) indicates that buoyancy, rather than initial momentum, dominates the plume rise. This is unsurprising as the only time when any initial momentum is generated is during shredding and turning; at those times, release temperatures are likely to be high, leading to a buoyant release.

4.5.2 Measurements

Figure 38 shows observations of total bacteria from Site B measured with the IOM monitor. The measurements are taken from six site visits. The receptor locations and the site activities varied over the series of visits.

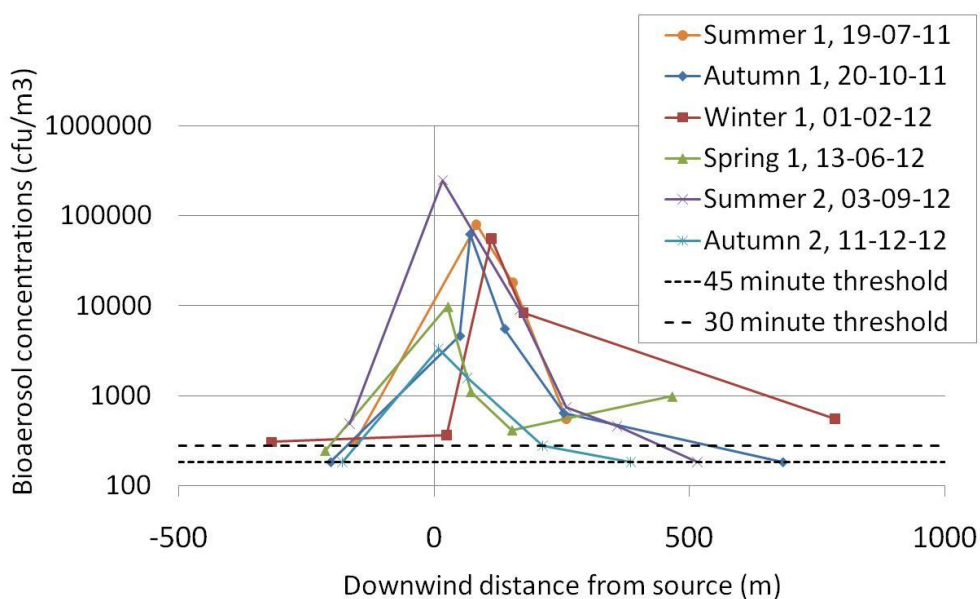


Figure 38 Observations of total bacteria from Site B measured with IOM monitor (Defra bioaersols dataset)

4.5.3 Model set up

4.5.3.1 Source configurations and efflux parameters

The model configuration is shown in Figure 39. The source dimensions estimate is based on tractor wheel tracks apparent in adjacent arable fields from the aerial image. The source was modelled as square in shape because its orientation to the wind direction is unknown (Figure 40). The horizontal dimensions of all of the modelled sources are 20 m by 20 m

Four area source and two volume source configurations were modelled; the parameters are summarised in Table 39. For the area source, two heights (2.5 and 5.0 m) and two sets of efflux conditions were considered; the efflux conditions represent a non-buoyant release (ambient temperature and zero exit velocity) and a buoyant release (35°C and 1 m/s exit velocity) in order to assess the impact of buoyancy. Note that this buoyant area source is similar in configuration to that recommended in Douglas (2013) with a lower exit velocity. The volume source was modelled at two heights (1.25 and 2.5 m) with depths of 2.5 and 5.0 m respectively.

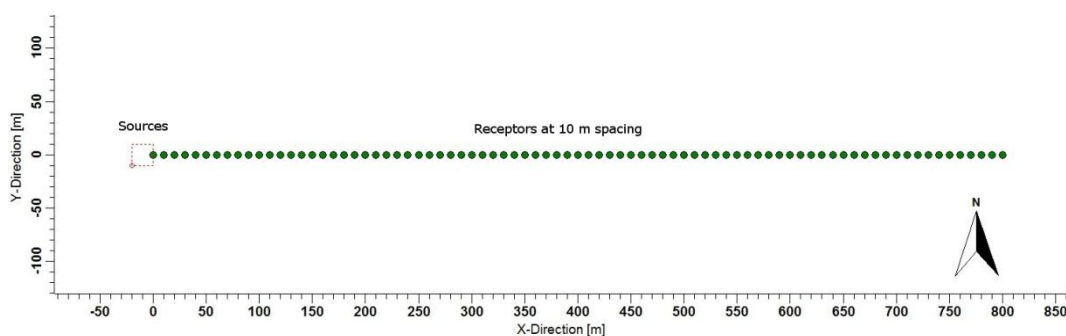


Figure 39 Study set up for Site B showing receptors (dark green dots)

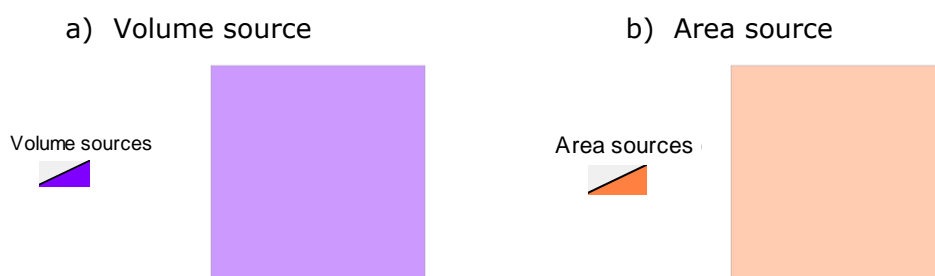


Figure 40 Source representations for Site B (Defra bioaerosol dataset)

Model results have been scaled to fit the maximum recorded concentration, which is the first or second measurement downwind of the source. Performance is assessed according to the models' ability to correctly predict observed concentrations further downwind.

The meteorology files are obtained from observations at the time of the monitoring periods studied. To ensure that the modelled plume is coincident with the receptors, the wind direction in the modelling has been set to 270 degrees.

Wind speeds below 1 m/s are set to 1 m/s. The ADMS default latitude of 51.9 degrees north is assumed; the roughness length is set to 0.2 m.

Table 39 Site B source parameter ranges

Idealised source type	Source dimensions (m)		Efflux parameters	
	Height (m)	Dimensions: Length (m) x Width (m) (x depth, m)	Temperature (°C)	Velocity (m/s)
Area	2.5	20 x 20	Ambient	0.0
Area	5.0	20 x 20	Ambient	0.0
Area	2.5	20 x 20	35	1.0
Area	5.0	20 x 20	35	1.0
Volume	1.25	20 x 20 (x 2.5)	n/a	n/a
Volume	2.5	20 x 20 (x 5.0)	n/a	n/a

Initial investigative modelling showed that deposition may be an important factor for bioaerosols and so this was included in the final modelling. Vestlund *et al.* (2014) states that bioaerosols can vary in size from 0.02 – 100 µm, although are typically less than 10 µm. The approach taken in the modelling is to consider a gaseous release followed by particulate releases of 1 µm, 10 µm and 100 µm. The corresponding deposition velocities and terminal velocities for these particle sizes, calculated by the model assuming a particle density of 1000 kg/m³, are shown in Table 40.

Table 40 Deposition and terminal velocities

Species	Deposition velocity (m/s)	Terminal velocity (m/s)
Gaseous	-	-
Particle, 1 µm	0.0014 – 0.0021	0.00003
Particle, 10 µm	0.0023 – 0.0330	0.00300
Particle, 100 µm	0.0024 – 0.0710	0.24000

4.5.3.1 Meteorological data

Onsite wind speed and wind direction measurements were taken. Estimates of cloud cover were also recorded at the site.

4.5.3.2 Output locations and settings

Eighty-one receptors were defined at 10 m intervals, starting at the centre of the eastern edge of the source and finishing 800 m downwind (Figure 39). The receptors are defined at a height of 1.5 m above ground level.

4.5.1 Results

Models were set up for each source parameterisation as outlined in Table 39, specifically, high and low level non-buoyant area, buoyant area and volume sources. Each of these were set up in turn for various parameterisations of deposition as outlined in Table 40; i.e. gaseous (no deposition), and as a particulate of varying size (and hence varying deposition and terminal velocity). These models were then run for each of the six datasets provided which cover

summer 2011, autumn 2011, winter 2012, spring 2012, summer 2012, and autumn 2012.

For each source, the average of the results over each height level was taken, so values were obtained for a buoyant area source, a non-buoyant area source, and a volume source for each deposition model. Results below are shown for summer 2012 (Figure 41) and winter 2012 (Figure 42). Figure 43 shows the results for winter 2012 without taking the average, i.e. the results are also presented separately for each of the source heights.

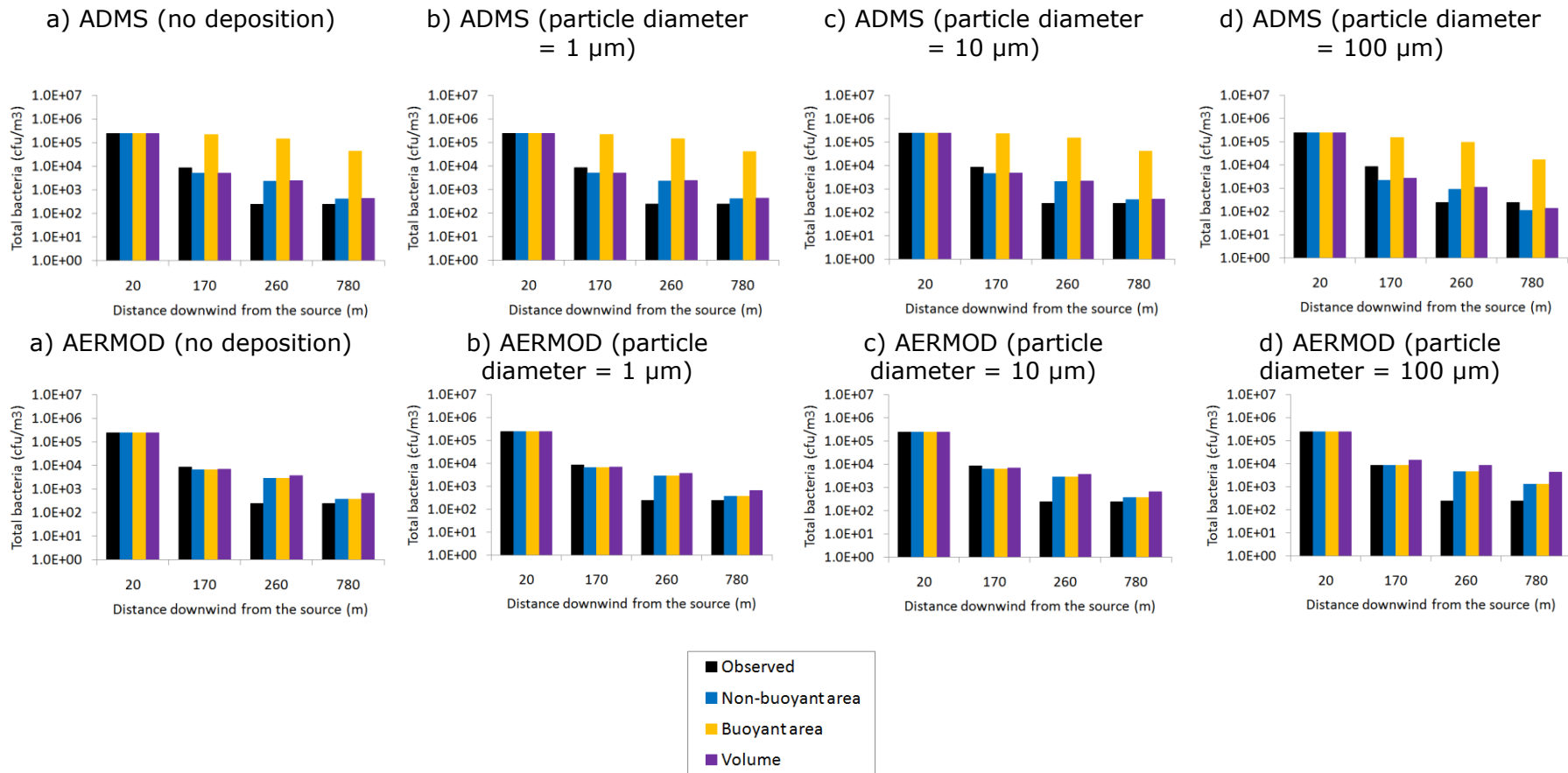


Figure 41 Summer 2: ADMS and AERMOD results from 03/09/12 normalised by the observed concentration at 20 m for cases where the bioaerosol is modelled as a gaseous and 1 µm, 10 µm, 100 µm particles (L-R)

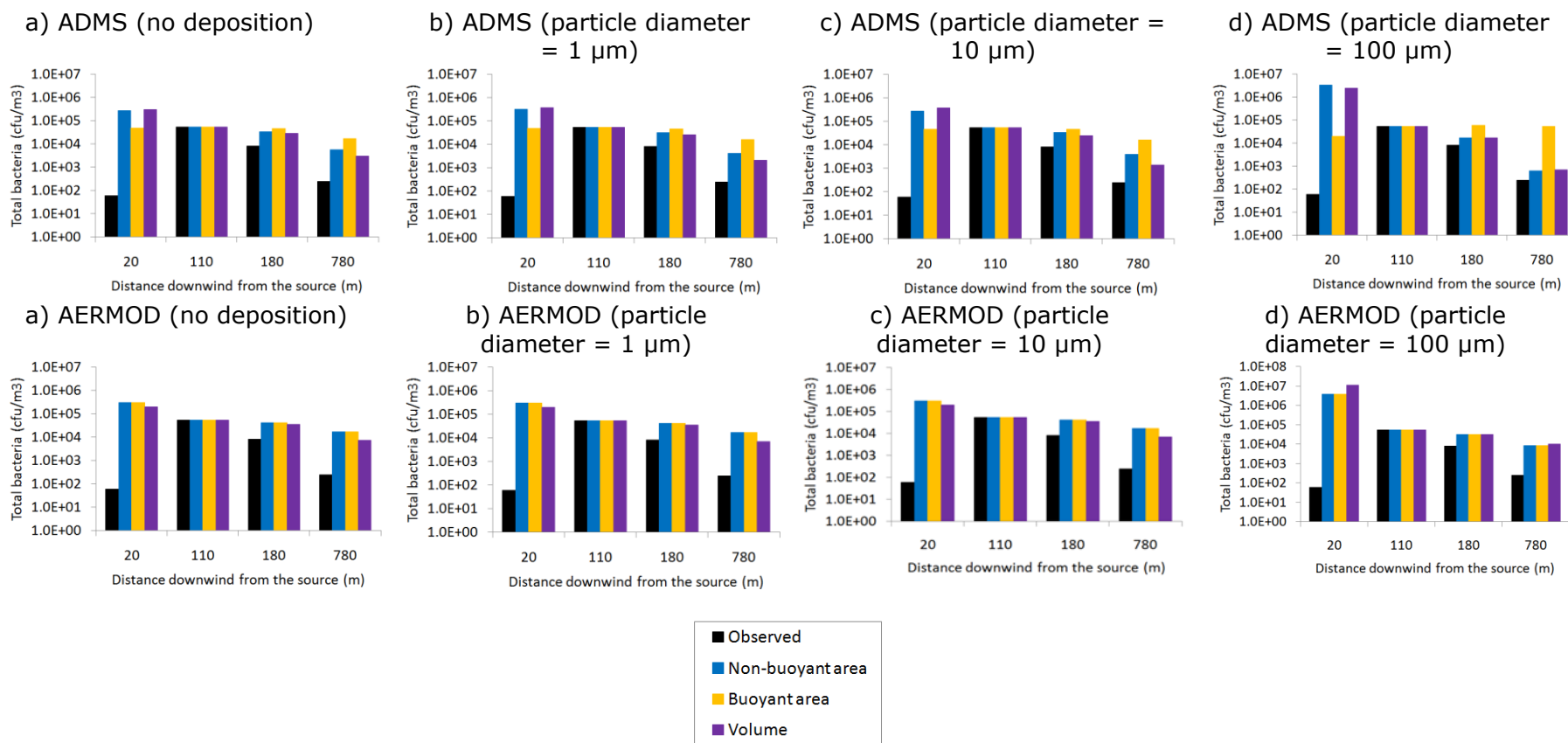


Figure 42 Winter 1: ADMS and AERMOD results from 01/02/12 normalised by the observed concentration at 110 m for cases where the bioaerosol is modelled as a gaseous and 1 μm, 10 μm, 100 μm particles (L-R)

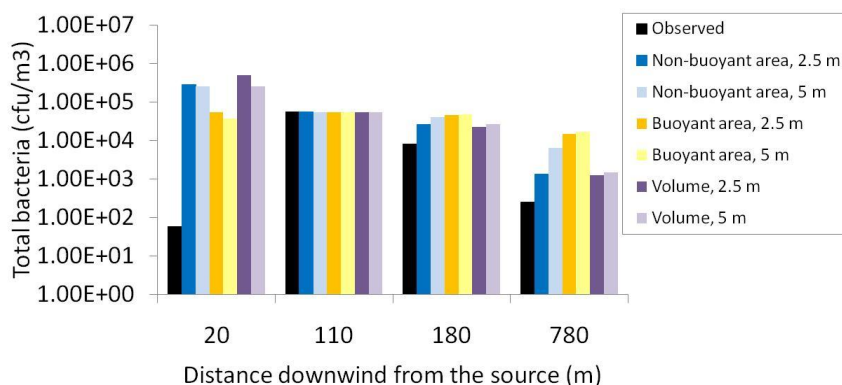


Figure 43 Winter 1: Results for 10 µm particles on 01/02/12 normalised by the observed concentration at 110 m including all source heights separately.

4.5.2 Discussion

4.5.2.1 Summer period

The observations for the summer period indicate that the momentum and buoyancy of the bacterial release from the site was unimportant because the concentration at the closest measurement to the site was the highest.

In terms of the modelling, all the non-buoyant source configurations behave in a similar way for the gaseous, 1 µm and 10 µm particulate cases; this is consistent with the idealised modelling for bioaerosol sources. Modelling the release with relatively high efflux parameters, similar to those recommended by Douglas (2013), leads to higher ADMS predicted concentrations which demonstrate less decay downwind (AERMOD does not model buoyancy for area sources). The lack of decay indicates that the turbulent entrainment of this relatively large area source has more influence on plume dispersion than the plume rise.

Two physical processes impact on near-ground concentrations when particulate deposition is modelled using ADMS and AERMOD. Firstly, as particulates are deposited on the ground, the amount of material in the plume is reduced, which leads to a reduction in near-ground concentrations; this process may be referred to as plume depletion. Secondly, the presence of particles results in the plume being denser than the ambient air, so plume height decreases, leading to an increase in near-ground concentrations; this process is known as gravitational settling. Thus plume depletion and gravitational settling have contrasting influences on near-ground concentrations.

For this study, modelling deposition using particle sizes of up to 10 µm has little impact on model results. When the particles are modelled using an absolute maximum particle size of 100 µm, concentrations predicted by ADMS are reduced, indicating that with ADMS, the influence of plume depletion dominates gravitational settling. Conversely, modelling this large particle size in AERMOD leads to an increase in predicted concentrations relative to the smaller particle size, indicating that the influence of gravitational settling outweighs the depletion in that model. Further inspection of the way in which each model allows for deposition would explain this difference in model behaviour.

Comparing the observed and modelled downwind concentration decay, the agreement is much better for the non-buoyant sources than for the buoyant source, and is in fact quite encouraging for both ADMS and AERMOD. For ADMS, it is not clear whether modelling the large particle size is an improvement to the modelling approach, but for AERMOD, the results for the large particle are worse than when little or no deposition is modelled.

4.5.2.2 *Winter period*

The observations for the winter period indicate that the bacterial release from the site was buoyant relative to the ambient conditions, because the concentration at the closest measurement to the site was much lower than those downwind. Alternatively, it may be that there was an issue with the measurement at this location.

For most source configurations, the downwind decay is not as well modelled by ADMS or AERMOD for this dataset. Further, when buoyancy is modelled using the ADMS area source, the very low observed value close to the source is not replicated.

As for the summer case, modelling with a particle size of up to 10 μm has little influence on results. For ADMS, modelling the very large particle size (100 μm) improves the model results significantly in the far field for the non-buoyant sources. However, for this case, the near-source model prediction increases, which is in contrast to the observations. The concentrations predicted for the buoyant area source are not significantly influenced by deposition. For AERMOD, results are also slightly improved with modelling a larger particle size, particularly for the area source configuration.

4.5.2.3 *Other periods*

Inspection of the model results on a case-by-case basis for the remaining periods did not add significantly to the conclusions drawn for this dataset. Given the number of measurements available for this dataset, however, it may be possible to perform some further analyses that may be of interest.

4.5.2.4 *Comments relating to the Douglas (2013) best practice modelling recommendations*

Following this bioaerosol model evaluation exercise and the idealised modelling reported in Section 3, the authors have a few comments relating to the Douglas (2013) best practice modelling recommendations. Specifically:

- The Site B model evaluation exercise indicates that allowing for dry deposition of particulates leads to a better representation of downwind concentration decay; this is in contrast to Douglas' suggestions that dry deposition should not be modelled.
- Clearly, it is only possible to back-calculate bioaerosol emission rates based on observations if measurements have been made at the site in question. In the absence of measured data, literature values of bioaerosol emission rates must be used.

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- By reviewing the literature, the authors agree that modelling windrows using a release temperature of approximately 29°C is reasonable; however, Douglas' suggested exit velocity of 2.95 m/s is unphysically large, and is likely to lead to an inaccurate prediction of ground-level concentrations in the far field.

5 TASK 4: PROJECT FINDINGS

The conclusions and recommendations of this study are put into context in Section 5.1; this section also includes a discussion relating to the achievement of project objectives. A summary of the overall project conclusions are presented in Section 5.2. Using these points as a guide, Section 5.3 outlines some guidance for good practice when modelling these non-point source types. A list of recommendations for further work is given in Section 5.4.

5.1 Context

The purpose of the current study was to assess the robustness (or otherwise) of common approaches to using numerical models to predict atmospheric pollutant concentrations due to emissions from non-point sources. Motivation for the study relates to the lack of evaluation of models of dispersion from non-point sources, in contrast to dispersion from point sources. Common examples of non-point sources that require assessment in terms of air quality include ammonia and particulate emissions from intensively farmed and free-range animals, and bioaerosol emissions from composting and water treatment plants; odour frequently emanates from both these source types. Road traffic sources are also classified as non-point sources, but are not the focus of the current work.

One of the reasons that non-point source modelling requires particular attention is that the majority of these emissions are emitted from near-ground level. Consequently, unless the release has sufficient initial momentum and/or buoyancy, the plume disperses close to ground level, which may result in high concentrations at human-exposure heights, even for relatively low emission rates. This is in contrast to elevated point sources where the plume does not impact on the ground until some distance downwind, by which time the concentrations are greatly reduced relative to exit concentrations. Therefore, whilst emission rates from point sources may be many times higher than those from non-point sources, their ground level impact may be lower.

Many of the sources relevant to this report are located in rural areas. On-site concentrations may be of minimal interest, and it is the mid- to far-field levels that are of concern, for example the impact at local villages and towns and designated SSSIs. In the current study, concentrations at up to 1 km from sources have been considered, although the majority of model evaluation has been for receptor distances less than 0.5 km. Beyond this distance, for releases with little initial momentum or buoyancy, the source description is unimportant.

For the most part, this study has achieved its objectives. The extensive literature review (Section 2) has highlighted a number of studies where non-point sources have been assessed by undertaking measurement campaigns and/or performing modelling. This has allowed the authors to list the idealised source types (line, area, volume, jet) used for modelling various real-world non-point sources (Tables 17 and 18). Further, these tables summarise the source parameter

ranges in terms of dimensions and efflux parameters; consequently, these tables will be of use to modellers performing similar studies.

The idealised modelling exercise (Section 3) was informative, highlighting similarities and differences between ADMS and AERMOD. Of particular importance has been the comparison of annual average concentrations at 100 m downwind of typical agricultural and bioaerosol sources (Figures 9 and 10); here the 100 m distance is assumed to be representative of a site boundary. This comparison showed that for releases without significant initial momentum or buoyancy, the non-point source type selected (line, area, volume) is unimportant for both ADMS and AERMOD; thus it may not be necessary to specify all the source parameters in detail if off-site concentrations only are of interest. The exception to this is any case where plume rise is important, when the initial momentum and buoyancy must be specified. Further, care must be taken when modelling ground-level line and area sources in AERMOD because predicted concentrations are much higher than those from other source types at this distance from the source.

Although many measurement campaigns have been undertaken recording pollutant concentrations in the vicinity of non-point sources (particularly relating to emissions from agriculture), the authors had difficulty obtaining the associated datasets. Of the four evaluation studies described in this report (Section 4), only the Whitelees dataset is robust with respect to dispersion model evaluation; this is because this field campaign was performed with the purpose of evaluating the SCAIL-Agriculture tool. The two other agricultural datasets used for model evaluation (Farm F and Farm G) were not designed for the purpose of dispersion model evaluation, and as such they were not sufficiently detailed to allow in-depth analyses; however, broad conclusions regarding modelling approaches can be derived. The lack of accurate bioaerosol emission rates for Site B resulted in an idealised modelling approach being taken for that model evaluation exercise.

The model evaluation exercises have been informative despite a relatively limited number of agricultural and bioaerosol source types having been considered. These studies suggest that when a moderately accurate source configuration is used together with on-site meteorological data, the dispersion models most commonly used in the UK for such studies (ADMS and AERMOD) predict period-average (as opposed to short-term statistic) concentrations that are within the $\pm 50\%$ of the measured values, as suggested by the EA guidance (AQMAU, 2010); specifically, refer to the modelled mean ammonia concentrations for Whitelees presented in Tables 31 and 32 for a source-receptor distance of 60 m. In terms of accurately predicting shorter-term values (for example hourly and maximum statistics for Whitelees given in Tables 31 to 34, and the averages over a few hours or a single day for Farms F and G, Figures 31 and 37, and Site B, Figures 41 and 42) the models must be configured accurately, for instance taking into account release dimensions and plume rise parameters.

When sources have initial momentum flux and buoyancy flux it is important that these are accounted for. Whilst an accurate value of plume exit velocity is always important as it affects both fluxes, an accurate temperature is only required when plume rise is buoyancy dominated. The relative importance of these release parameters has been assessed during the model evaluation exercise. For the Whitelees case, where fans within upward pointing cowls are employed, plume rise is for the most part driven by the initial momentum of the release; initial momentum also contributes to the plume structure for Farm F, which has an End Ventilation System. However, for both these studies, for cold, stable meteorological conditions, buoyancy dominates plume rise. Buoyancy is always the dominating influence on plume rise for Farm G, where exit velocities are significantly reduced by the presence of a baffle.

For each of the agricultural evaluation studies, the emission rates derived from on-site measurements have been compared to the industry standard values, calculated from the number of animals within the sheds. The comparisons are reasonably encouraging. At Whitelees, the measured emission rate is 2-3 times higher than the industry standard, but for Farms F and G, where it has been assumed that PM_{10} is 20% of dust, the measured emission rates are up to 40% lower than the industry standard.

5.2 Overall conclusions

The overall conclusions from this study are:

1. If near-field (less than 100 m) concentrations relating to emissions from agricultural and bioaerosol sources are of interest, detailed information relating to the source location, dimensions and exit conditions need to be available and accounted for in the modelling.
2. At distances greater than 100 m, source dimensions are less important. Efflux conditions may be important, depending on the buoyancy and momentum of the release.
3. When point sources are modelled with a building, the predicted modelled concentrations are sensitive to the source / building configuration, particularly when using ADMS. Using a non-point source to represent typical agricultural and bioaerosol sources gives, in most cases, predictions that are similar on average to the 'point sources with buildings' model set up, if appropriate buoyancy has been allowed for. The non-point source results have less variation because the dispersion is not influenced by the presence of the building.
4. The impact on dispersion of low-level agricultural sheds and buildings at waste sites may not be very important when multiple sources are modelled because a) they are low so building downwash is minimal and b) the increased turbulence caused by the building has little effect because the sources are already spread out.

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5. ADMS is able to model line, area, volume and jet sources. Of these non-point source types, volume sources should not be used if the source has significant buoyancy or momentum.
 6. AERMOD is able to model line, area, volume and horizontal wind-aligned jet sources. Of these non-point source types, neither volume, line nor area sources should be used if the source has significant buoyancy or momentum^{***}. The jet source should only be used in cases where the release is wind aligned.
 7. When low-level line and area sources are modelled using AERMOD version 14134, the predicted concentrations appear to be inconsistent with other source types in the mid to far field (Figures 9 and 10).

5.3 Good practice guidance

This section gives suggestions for dispersion modelling good practice when using non-point sources to represent releases from, for example: mechanically and naturally ventilated animal sheds; free range grazing areas; composting processes; and waste water sites. The recommendations relate directly to non-point source modelling using ADMS and AERMOD but may be applicable to other dispersion models and to the use of point sources.

Prior to configuring the dispersion model, in addition to data relating to emissions and source dimensions, the following information should be collated:

- The location of the receptors of interest; specifically, are they close to (less than approximately 100 m) or far from (greater than approximately 100 m) the source?
- Metrics of interest: period average or short term?
- The exit velocity of the release, including any temporal variations if these data are available.
- The temperature of the release, including any temporal variations if these data are available.

Once this information has been made available, the flow chart given in Figure 44 can be used to decide on the level of detail required for the modelling. Note that when modelling roof vents on agricultural sheds, it is usually advisable to represent the releases using one or more point sources; for such studies, buildings should be included.

^{***} AERMOD version 15181 (released towards the end of July 2015) includes an option for modelling buoyant line sources, but this model option has not been assessed as part of this project.

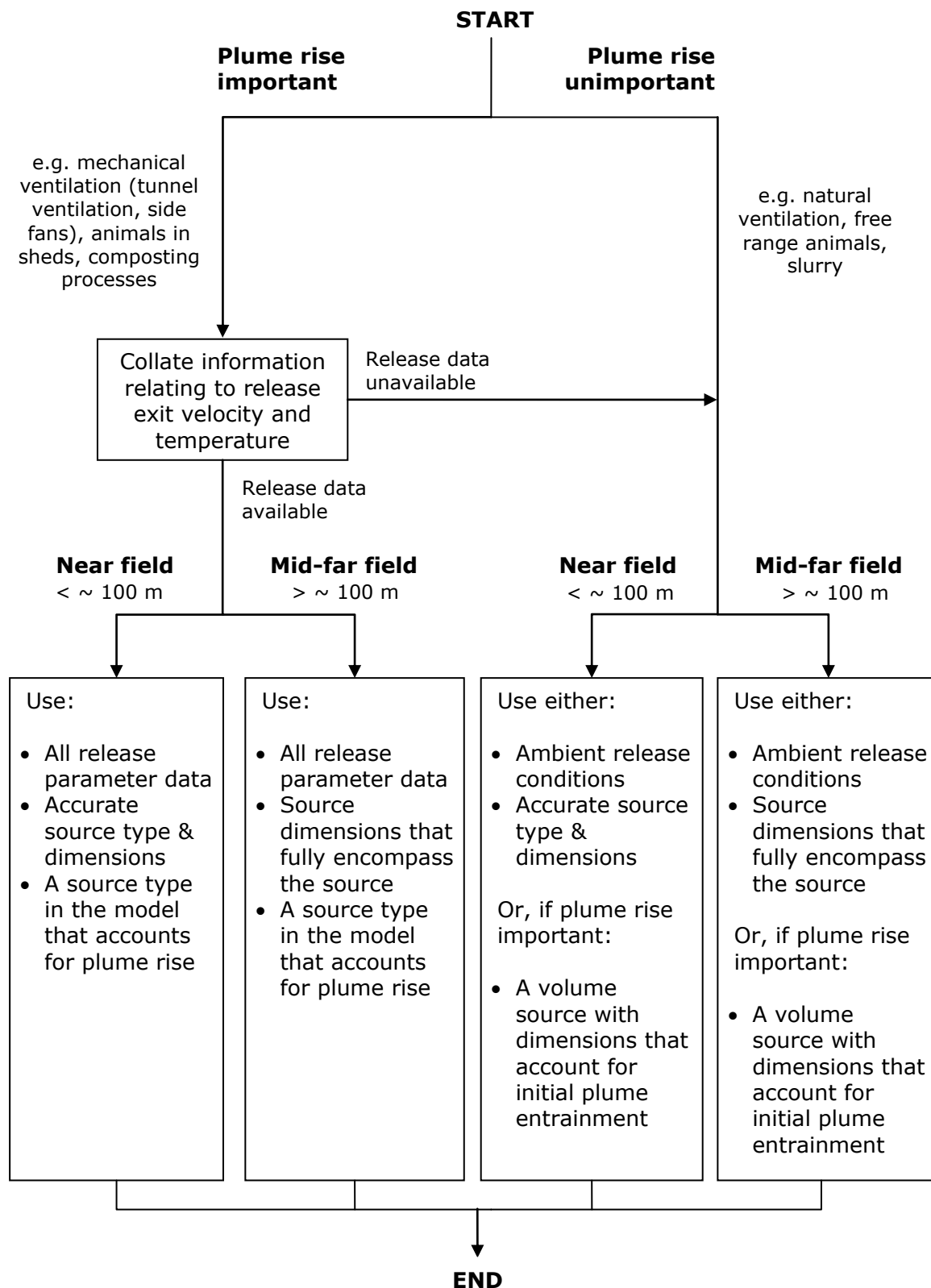


Figure 44 Best practice flow chart.

5.4 Recommendations for further work

Recommendations for further work in this study area include:

Recommendation 1 Other dispersion models listed as suitable for modelling non-point sources in Table 9 should be run to assess their generic behaviour and their performance in the case studies, in addition to ADMS and AERMOD.

Recommendation 2 The model developers of ADMS and AERMOD should seek to develop their building modules to allow for dispersion of non-point sources.

Recommendation 3 Existing technical guidance documents should be updated to reflect the conclusions of this study.

Recommendation 4 A project should be undertaken to collate robust datasets that are suitable for dispersion model evaluation exercises. This applies not only to agriculture and bioaerosol studies, but also to other source types, for example, road traffic and industrial sources. Similar initiatives include the Model Validation Toolkit, which has been put together as part of the Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes conferences, and the AERMOD model evaluation databases available for download from the US EPA website.

Recommendation 5 Specifications for future measurement campaigns should include the requirement for compilation of the data, with associated metadata, into a format that is transferable to others, so that it can be used for further analyses. Improved communication and collaboration between organisations would facilitate sharing of available data.

Recommendation 6 In order to improve and standardise the approach to dispersion modelling of bioaerosol emissions, research into the physical processes that occur when these pollutants disperse is required. Such research should result in guidance on recommended particle size values, with associated mass fractions, and coagulation rates.

Recommendation 7 The exact times and locations of the Defra poultry study measurements should be made available and used to re-model these cases. It is likely that model performance would improve but also the number of data points available for model evaluation purposes may increase. The remaining six Defra poultry study datasets should be inspected in order to decide if they are suitable for model evaluation purposes.

Recommendation 8 Additional measured bioaerosols (*Aspergillus fumigatus*; gram-negative bacteria; glucans; endotoxins) for Site B should be assessed in terms of their suitability for modelling. The remaining three Defra bioaerosol study datasets should be inspected in order to decide if they are suitable for model evaluation purposes. Additional modelling should be conducted for suitable datasets.

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APPENDIX A

This appendix presents the ADMS and AERMOD formulations for point, area, volume and jet sources.

A1 Point sources

Although the focus of this work is non-point sources, it is helpful to inspect the formulations for point sources in the different models, as in most cases the non-point source definitions are derived from the point source equations.

Sections A1.1 and A1.2 give point source definitions for ADMS and AERMOD. Both ADMS and AERMOD are able to model the influence of buildings on dispersion when point sources are modelled.

A1.1 ADMS

The concentration, C , at a location downwind of a point source is represented in ADMS by:

$$C = \frac{Q_s}{2\pi\sigma_y\sigma_z U} \exp\left(\frac{-y^2}{2\sigma_y^2}\right) \left\{ \exp\left(\frac{-(z-z_p)^2}{2\sigma_z^2}\right) + \exp\left(\frac{-(z+z_p)^2}{2\sigma_z^2}\right) + \text{reflection terms} \right\}$$

where Q_s is the source emission rate in mass units per second; σ_y and σ_z are the lateral and vertical plume spread parameters respectively in metres; U is the wind speed at the plume centreline height in m/s; z is the output height above ground in metres; y is the lateral distance from the plume centreline in metres; and z_p is the plume centreline height in metres.

A1.2 AERMOD

Point source concentrations are calculated by numerically integrating over the area with a double integral in the downwind and crosswind directions.

$$C = \frac{Q_A}{2\pi U_s} \int_x \frac{VD}{\sigma_y\sigma_z} \left(\int_y \exp\left(\frac{-y^2}{2\sigma_y^2}\right) dy \right) dx$$

Where Q_A is source emission rate in mass units per square metre per second and D is now a function of x . V is a vertical term given by:

$$V = \exp\left[-0.5\left(\frac{z_r - h_e}{\sigma_z}\right)^2\right] + \exp\left[-0.5\left(\frac{z_r + h_e}{\sigma_z}\right)^2\right] \\ + \sum_{i=1}^{\infty} \left\{ \exp\left[-0.5\left(\frac{H_1}{\sigma_z}\right)^2\right] + \exp\left[-0.5\left(\frac{H_2}{\sigma_z}\right)^2\right] + \exp\left[-0.5\left(\frac{H_3}{\sigma_z}\right)^2\right] \right. \\ \left. + \exp\left[-0.5\left(\frac{H_4}{\sigma_z}\right)^2\right] \right\}$$

where:

$$h_e = h_s + \Delta h$$

$$H_1 = z_r - (2iz_i - h_e)$$

$$H_2 = z_r + (2iz_i - h_e)$$

$$H_3 = z_r - (2iz_i + h_e)$$

$$H_4 = z_r + (2iz_i + h_e)$$

z_r = receptor height above ground (flagpole) (m)

z_i = mixing height (m)

h_s = stack height (m)

Δh = plume rise (m)

i = summing index

A2 Area sources

Sections A2.1 and A2.2 give area source definitions for ADMS and AERMOD. When area sources are modelled, the influence of buildings on dispersion is not considered in either ADMS or AERMOD.

A2.1 ADMS

The concentration is calculated by decomposing the source into source elements of crosswind line sources. With x in the downwind direction and y crosswind direction, each source element gives a concentration of $\bar{c}(x, y, z)$:

$$\bar{c}(x, y, z) = \frac{\bar{Q}_s}{2\sqrt{2\pi}\sigma_z U} \exp\left(-\frac{(z - z_s)^2}{2\sigma_z^2}\right) \times \left[\operatorname{erf}\left(\frac{y + \frac{L_s}{2}}{\sqrt{2}\sigma_y}\right) - \operatorname{erf}\left(\frac{y - \frac{L_s}{2}}{\sqrt{2}\sigma_y}\right) \right] + \text{reflection terms}$$

where \bar{Q}_s is the source element emission rate in mass units per metre per second, L_s is the line source length and the other symbols are as defined in Section A1.

A2.2 AERMOD

Area source concentrations are calculated by numerically integrating over the area with a double integral in the downwind and crosswind directions.

$$C = \frac{Q_A}{2\pi U_s} \int_x \frac{VD}{\sigma_y \sigma_z} \left(\int_y \exp\left(\frac{-y^2}{2\sigma_y^2}\right) dy \right) dx$$

Where Q_A is source emission rate in mass units per m^2 per second and D is now a function of x .

A3 Volume sources

Sections A3.1 and A3.2 give volume source definitions for ADMS and AERMOD. When volume sources are modelled, the influence of buildings on dispersion is not considered in either ADMS or AERMOD.

A3.1 ADMS

The concentration is calculated by decomposing the source into source elements of crosswind vertical slices. Each source element gives a concentration of $\bar{C}(x, y, z)$:

$$\bar{C}(x, y, z) = \frac{\bar{Q}_s}{4U} \left[\operatorname{erf} \left(\frac{y + L_s/2}{\sqrt{2}\sigma_y} \right) - \operatorname{erf} \left(\frac{y - L_s/2}{\sqrt{2}\sigma_y} \right) \right] \times \left[\operatorname{erf} \left(\frac{z + L_V/2 - z_s}{\sqrt{2}\sigma_z} \right) - \operatorname{erf} \left(\frac{z - L_V/2 - z_s}{\sqrt{2}\sigma_z} \right) \right]$$

where \bar{Q}_s is the source element emission rate in mass units per square metre per second, L_s is the slice length and L_V is the height and the other symbols are as defined in the previous sections.

A3.2 AERMOD

Volume sources are modelled as point sources and so follow the same Gaussian equation as given in A1.2. Volume sources have initial lateral and vertical plume sizes, which are calculated by adding the squares of the initial and ambient plume sizes:

$$\sigma_y^2 = \sigma_{yl}^2 + \sigma_{yo}^2$$

where σ_{yl} is the ambient lateral plume size, σ_{yo} is the initial horizontal plume size and σ_y is the resulting lateral plume size.

A4 Jet / horizontal point sources

Sections A4.1 and A4.2 give jet / horizontal point source definitions for ADMS and AERMOD. When jet sources are modelled, the influence of buildings on dispersion is not considered in ADMS; AERMOD uses a different formulation for the horizontal point source when buildings are present.

A4.1 ADMS

ADMS can model jets with an exit velocity and at a release angle defined in spherical coordinates. When the direction of the release is upstream the position of the plume centre at downwind coordinate x can be multi-valued. If the plume centre is at upwind coordinate x at times $t = t_1$ and $t = t_2$ then the concentration is given by:

$$C = \frac{Q}{2\pi u_{c1} \sigma_y(t_1) \sigma_z(t_1)} \exp\left\{-\frac{(y - y_p(t_1))^2}{2\sigma_y(t_1)^2}\right\} \exp\left\{-\frac{(z - z_p(t_1))^2}{2\sigma_z(t_1)^2}\right\} \\ + \frac{Q}{2\pi u_{c2} \sigma_y(t_2) \sigma_z(t_2)} \exp\left\{-\frac{(y - y_p(t_2))^2}{2\sigma_y(t_2)^2}\right\} \exp\left\{-\frac{(z - z_p(t_2))^2}{2\sigma_z(t_2)^2}\right\} \\ u_c = \max\left(\sqrt{u_p^2 + v_p^2}, \sigma_u(z_p)\right)$$

Where y_p and z_p are the lateral and vertical plume centre coordinates, u_p and v_p are the downwind and crosswind plume velocity components and σ_u is the longitudinal turbulence at the plume centreline height; u_{c1} and u_{c2} refer to the horizontal plume speed at times t_1 and t_2 respectively.

A4.2 AERMOD

AERMOD models horizontal release wind-aligned point sources. These are taken as point sources with very low exit velocity (0.001 m/s), and stack diameter sufficiently large to ensure a correct flow rate; stack tip downwash is not modelled. When horizontal point sources are modelled with buildings, the horizontal exit velocity of the release is set to be the user-defined value.

APPENDIX B

This appendix summarises the different methodologies that ADMS and AERMOD apply to modelling: dispersion around buildings, plume rise and the temporal variation of emissions (Table 41); dry and wet deposition and meteorology (Table 42). Table 43 gives more details of the differences between the ADMS and AERMOD building modules.

Table 41 Different modelling approaches in ADMS and AERMOD: building effects, plume rise and temporal variation in emissions.

	ADMS	AERMOD
Building effects	Both models have a broadly similar approach of calculating wake and cavity regions due to a building, incorporating entrainment of the plume in to the cavity, and modelling changes in turbulence due to the building, including downwash, but the technical details and formulation for various parts of the model differ. For example, the calculation of the cavity height, wake dimensions, streamline deflection, turbulent effects, plume spread, and cavity and wake concentrations all differ. Further details are given in Table 43. Also refer to Robins (2000).	
Plume rise due to buoyancy	<p>Uses a top-hat integral model, requiring the solution of conservation equations for mass, momentum, enthalpy and emitted material. Entrainment is described by an entrainment velocity with separate components due to the plume's relative motion and ambient turbulence. Assumes release is a perfect gas. Inversions can be treated and gravitational settling accounted for if particulate deposition is modelled.</p> <p>Plume rise is not modelled for volume sources.</p> <p>A 'lift off' condition for ground level line and area sources is imposed, such that the release must have sufficient buoyancy and momentum to leave the ground to allow plume rise to be modelled; further details are given in APPENDIX C.</p>	<p>Uses Briggs empirical expressions for the convective boundary layer. Use an iterative approach based on Weil (1988) to account for decrease in buoyancy with height for the stable boundary layer with modifications made for small buoyancy frequencies and for small wind speeds.</p> <p>Plume rise is only modelled for point sources.</p>
Temporal variations in emissions	<p>Temporally varying emissions can be modelled by specifying emission factors varying by hour of day or varying by month, or both. Hour-of-day factors may be specified for each day of the week (168 factors) or for weekdays, Saturdays, Sundays (72 factors). Wind-direction dependent processes may also be included. Alternatively hourly-varying emission rates, temperatures/densities, volume flow rates/exit velocities, diameter and initial H₂O mixing ratio may be specified separately.</p>	<p>Similarly to ADMS, emission factors can be specified or hourly-varying emission rates, exit temperatures and exit velocities can be given (the last two for point sources only). In AERMOD emission factors can be specified for a wide variety of time periods, i.e. by season, month, hour-of-day (weekdays, Saturdays, Sundays), hour-of-day (each day) or various combinations of these options.</p>

Table 42 Different modelling approaches in ADMS and AERMOD: dry deposition, wet deposition and meteorology

	ADMS	AERMOD
Dry Deposition	Gases Dry deposition rate given by product of deposition velocity and ground level airborne concentration. The deposition velocity for gases is either specified by the user or estimated by the model as a reciprocal sum of the aerodynamic, sub-layer and surface layer resistances, which depend on the reactivity of the pollutant species being modelled.	A similar approach to ADMS is taken to obtain the deposition velocity as a reciprocal sum of resistances but to calculate these deposition parameters the user specifies season, land use, diffusivity in air, diffusivity in water, cuticular resistance and Henry's constant; or the 'reactivity factor' and green leaf area index can be specified. Alternatively, the deposition velocity may be specified directly.
	Particles The deposition velocity for particles comprises the diffusion and settling velocity which are either specified directly by the user or calculated from particle densities, diameters and mass fractions.	For large particles specify mass fraction, densities and diameters to calculate deposition velocities. For small particles, specify fine mass fraction and mass-mean aerodynamic particle diameter to calculate weighted average deposition velocity of fine and coarse modes.
Wet Deposition	Wet deposition is calculated either by defining a washout coefficient or by calculating the washout from the precipitation rate.	Calculated from precipitation rate and deposition parameters (e.g. Henry's constant) or calculates a washout coefficient for particles depending on the scavenging rate, particle diameter etc.
Meteorology and boundary layer parameterisation.	AERMOD and ADMS are broadly the same as both use Monin-Obukhov similarity theory to describe plume dispersion, as opposed to Pasquill-Gifford categories. There are some differences between the models; e.g. the expressions for the wind speed within the boundary layer are not the same, though the resultant wind speed profiles are virtually identical. The boundary layer height and the heat fluxes obtained are different, though there is no general trend. There are other differences. An exhaustive list is not given here, but some of the main known differences are highlighted below.	
	Considers stable/neutral/convective meteorology.	Considers stable/convective meteorology.
	Solves the full coupled system of equations iteratively to calculate u^* and the Monin-Obukhov length.	Solves the full coupled system of equations iteratively to calculate u^* and the Monin-Obukhov length in convective conditions, but uses an approximation in the stable case leading to a limit in the reciprocal of the Monin-Obukhov length.
	Assumes a constant value for the buoyancy frequency.	Requires an upper air profile to calculate some meteorological parameters such as the buoyancy frequency from observations.
	Determines daylight to be when the insolation is non-zero.	Determines daylight to be the time when the boundary layer is convective (which is when the heat flux is positive)
	Uses Priestley-Taylor parameter for moisture availability	Uses midday Bowen ratio

Table 43 Summary of differences between the ADMS and AERMOD building modules

Item	Comparison	Notes
Mean flow	Different	Different expressions are used: ADMS depends on buildings properties and location within the wake; AERMOD uses a fractional deficit of 0.7 modified by the location within the wake.
Creation of effective building from multiple buildings	Different	Different methods are used: ADMS applies an algorithm that assesses each building in the vicinity of the 'main' building in terms of its relative height and crosswind separation; AERMOD combines buildings if they are separated by less than 5 times a characteristic dimension of each building.
Number of flow regions	Different	A different number of flow regions are considered: ADMS models five regions whereas AERMOD has two regions in addition to a smoothing region.
Cavity length	Identical	n/a
Cavity height	Different	Identical for the reattachment case, similar concept but different expression for the other case(s).
Wake height/width	Different	Similar concept but different expressions: AERMOD depends solely on effective building properties; the ADMS formulation includes a dependence on meteorological data.
Streamline deflection	Different	Similar concepts but different expressions used.
Turbulence	Different	Different expressions are used: ADMS assumes the turbulent velocity variances increase in proportion to the wake-averaged surface shear stress; AERMOD derives the turbulent velocity from empirical expressions and ambient values.
Plume spread	Different	Different approach: ADMS calculates the wake-affected spread parameters from non-building parameters accounting for differences in turbulence, velocity and streamline convergence; AERMOD models a p.d.f. growth in the near wake transitioning to eddy diffusivity growth in the far wake.
Cavity concentration	Different	Similar approach: both models determine a fraction entrained into the cavity, but the expressions used for the amount entrained and for the resulting cavity concentrations differ.
Wake concentration	Different	Similar approach: both models have contributions from the non-entrained part of the original plume and a ground based plume from the cavity region; the formulation of those expressions differs.

APPENDIX C

This appendix gives details of the 'lift-off' condition used in ADMS.

In ADMS, the plume rise module (ADMS Technical Specification document, P11/02, 2013) is used to calculate plume rise from line and area source types in addition to point sources; volume sources are always considered to be passive in ADMS. AERMOD does not take plume rise into account for any non-point sources.

ADMS imposes a 'lift off' condition for ground level line and area sources, such that the release must have sufficient buoyancy and momentum to leave the ground to allow plume rise to be modelled. The following thresholds are used:

$$F_M > 2 \text{ or } F_B > 0.01 \quad (10)$$

where F_M and F_B are the non-dimensional momentum and buoyancy fluxes respectively:

$$F_M = \frac{\rho_s w^2}{\rho_a U^2} \quad (11)$$

$$F_B = \frac{g\pi D w (\rho_a - \rho_s)}{4\rho_a U^3} \quad (12)$$

Here, w is the emission velocity, ρ_s the emission density, ρ_a the density of the ambient air and U the wind speed at 10 m. D is a source dimension. For an area source it is the square root of the source area and for a line source it is the minimum dimension, which will usually be the line width rather than the line length.

For area sources that are large in cross-section the assumption that the emission behaves like one plume, if it has sufficient momentum and buoyancy, is not very accurate. The emission will not in practice behave as a single bent over plume.

The default value for the emission velocity or volume flow rate from a line or area source in the model interface is zero which turns off the plume rise module. This default value has been adopted to reflect the fact that in practice such sources e.g. road traffic, quarries, will not usually have significant plume rise.

APPENDIX D

This appendix presents the idealised modelling results from ADMS and AERMOD. Section D1 presents the results for agricultural source types and Section D2 presents the results for bioaerosol source types.

D1 Agricultural source types

Section D1.1 presents the results for single meteorological conditions and Section D1.2 presents the annual average results.

D1.1 Single meteorological conditions

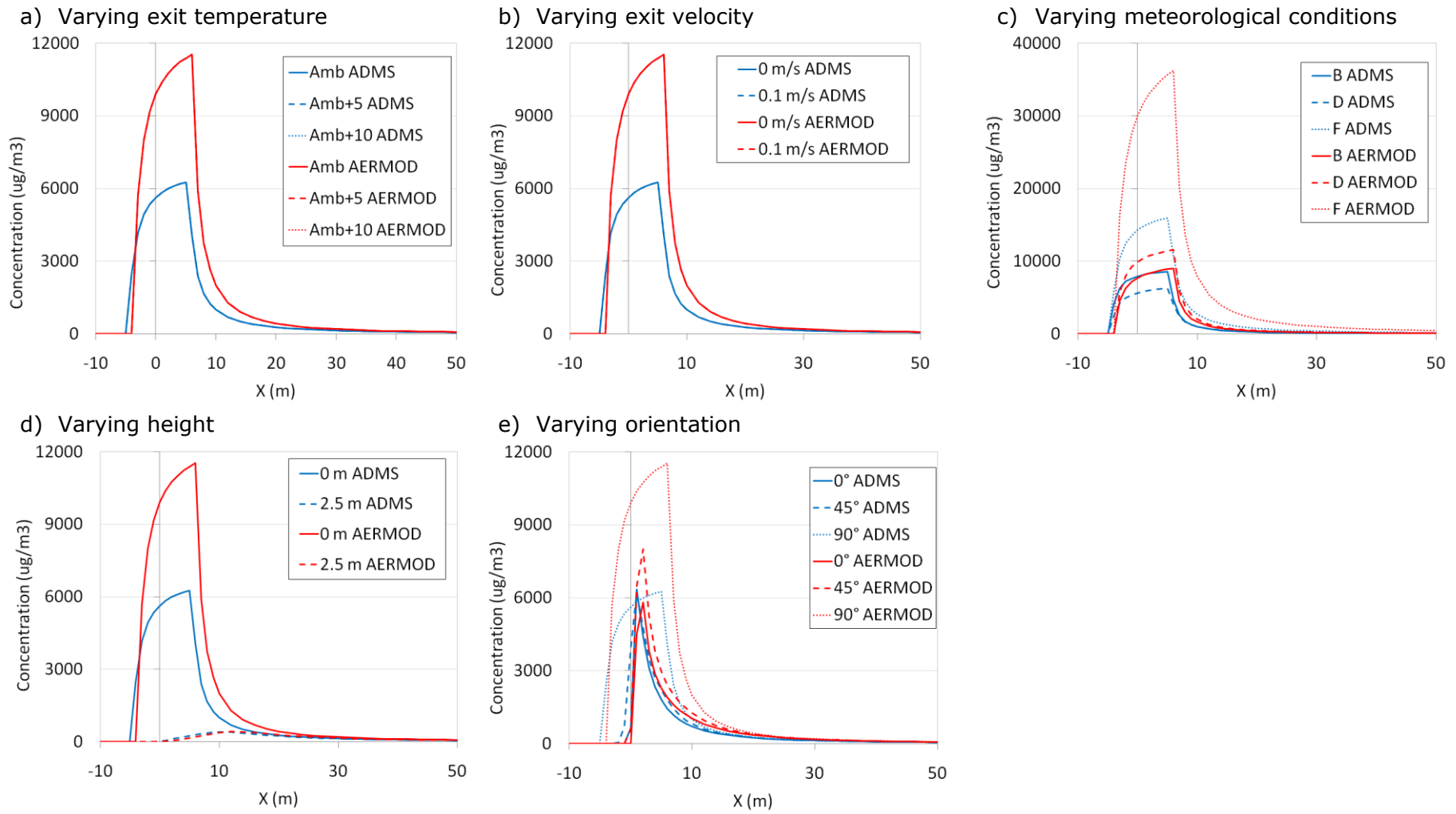
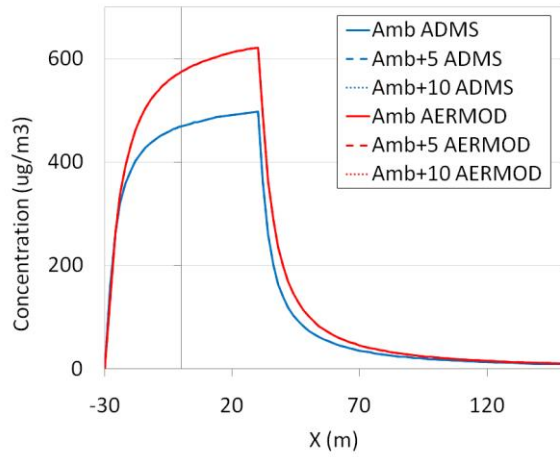
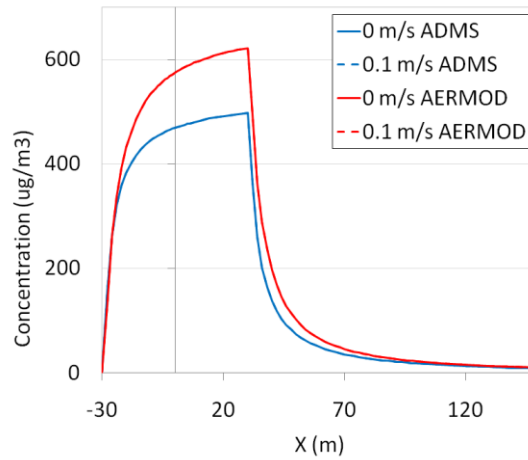


Figure 45 Agricultural single meteorological condition line source results from ADMS and AERMOD

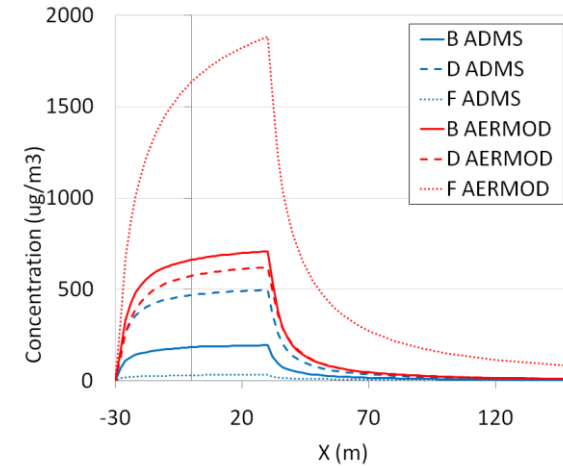
a) Varying exit temperature



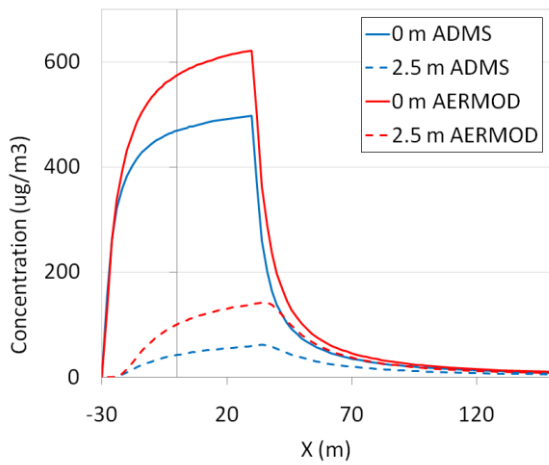
b) Varying exit velocity



c) Varying meteorological conditions



d) Varying height



e) Varying orientation

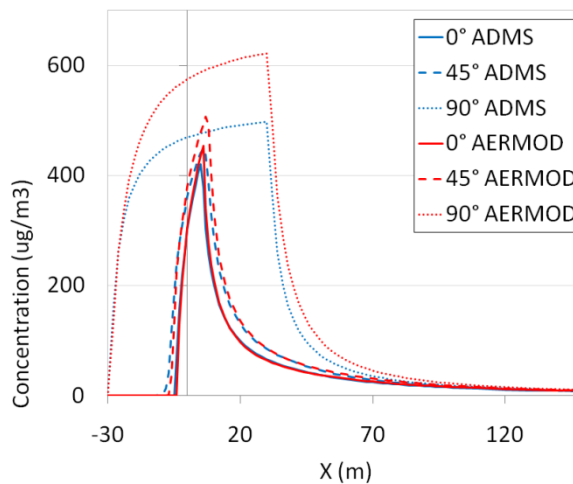


Figure 46 Agricultural single meteorological condition area source results from ADMS and AERMOD

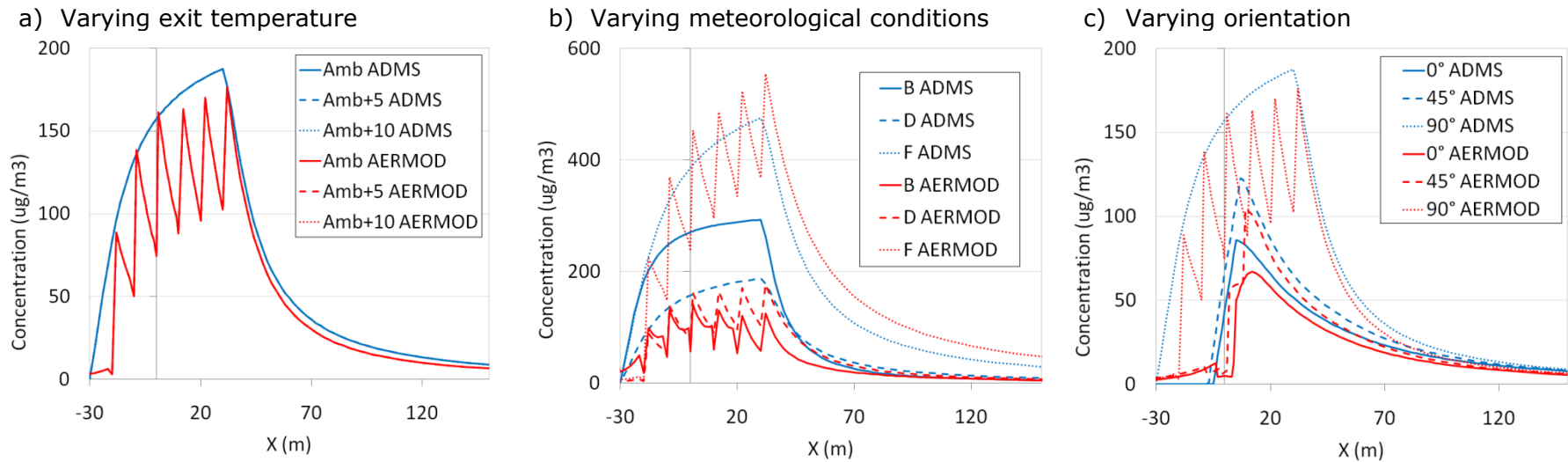


Figure 47 Agricultural single meteorological condition volume source results from ADMS and AERMOD

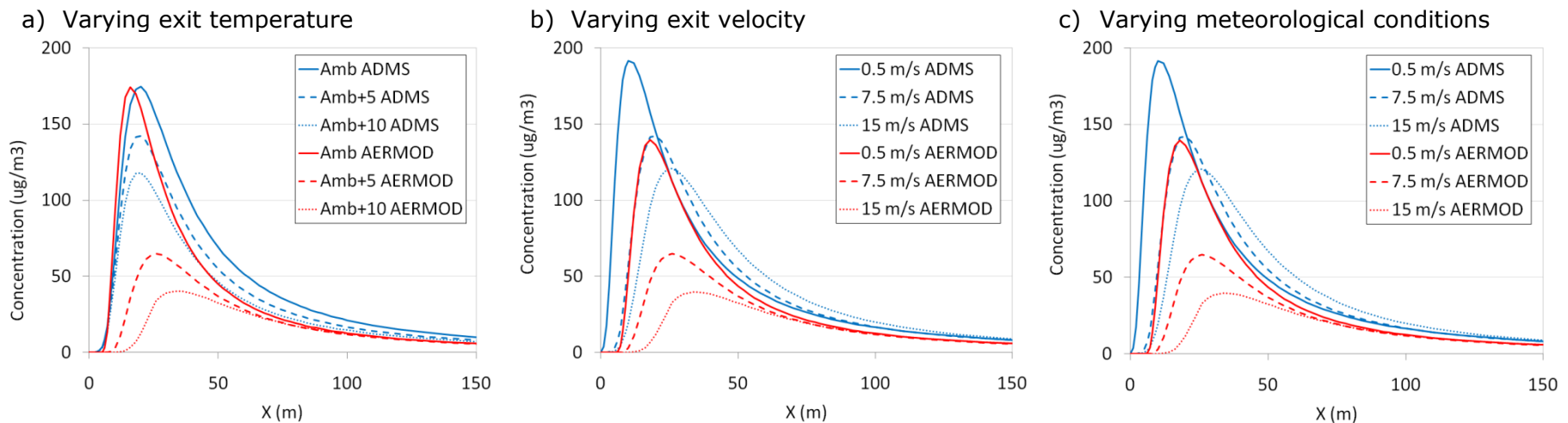
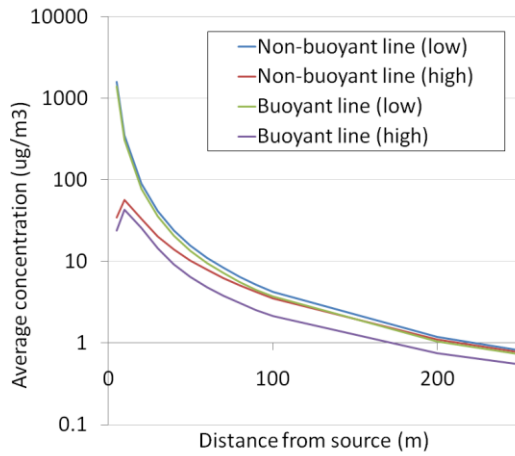


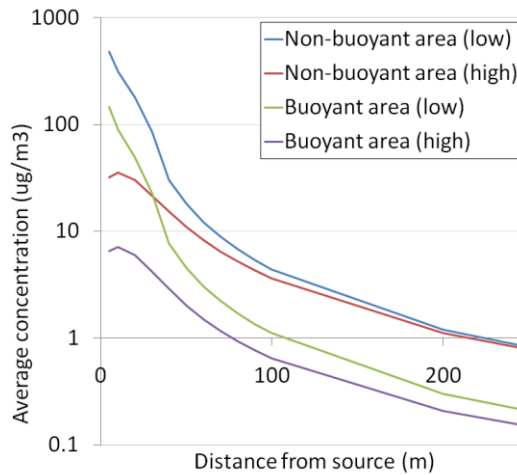
Figure 48 Agricultural single meteorological condition jet source results from ADMS and AERMOD

D1.2 Annual averages

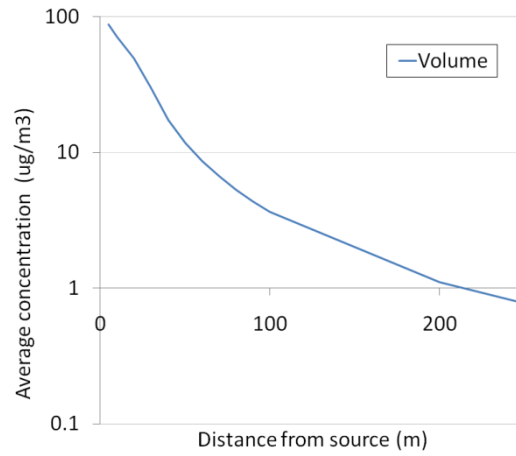
a) ADMS line source (agricultural sources)



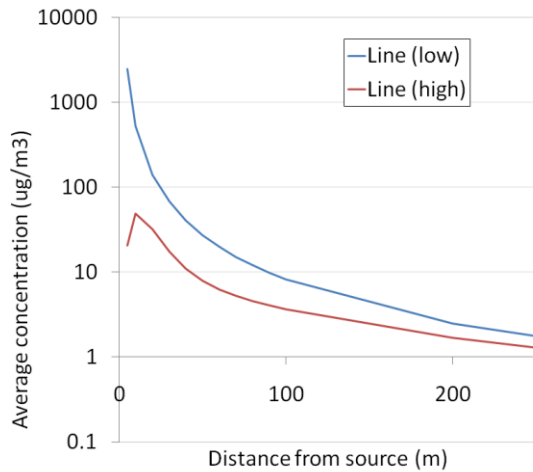
b) ADMS area source (agricultural sources)



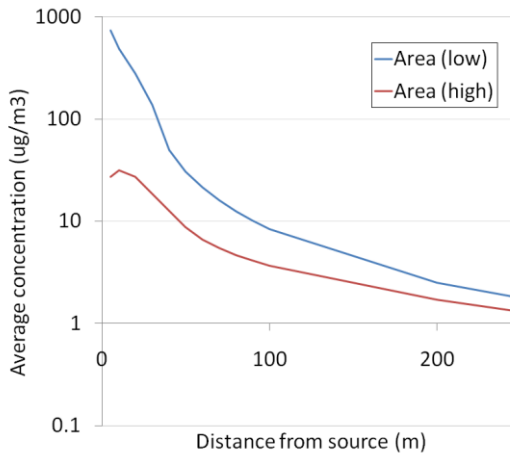
c) ADMS volume source (agricultural sources)



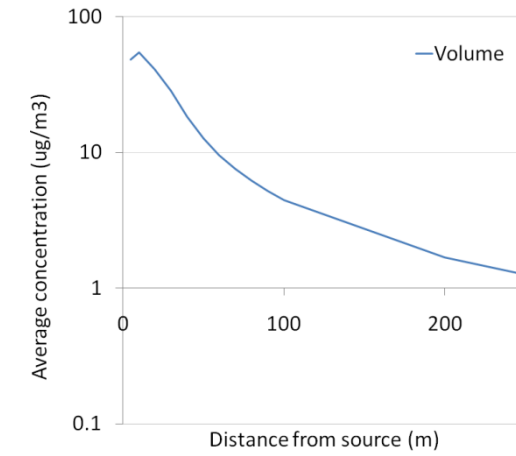
d) AERMOD line source (agricultural sources)



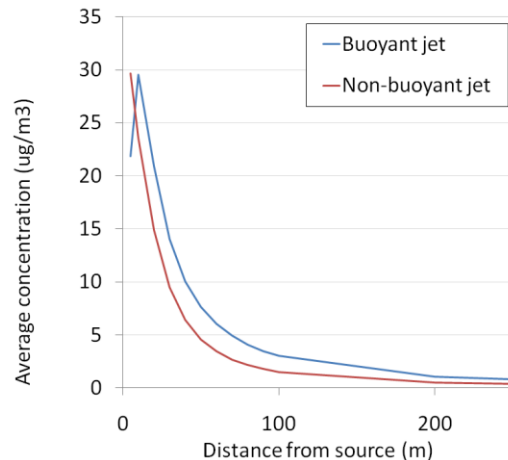
e) AERMOD area source (agricultural sources)



f) AERMOD volume source (agricultural sources)



g) ADMS jet source (agricultural sources)



h) AERMOD jet source (agricultural sources)

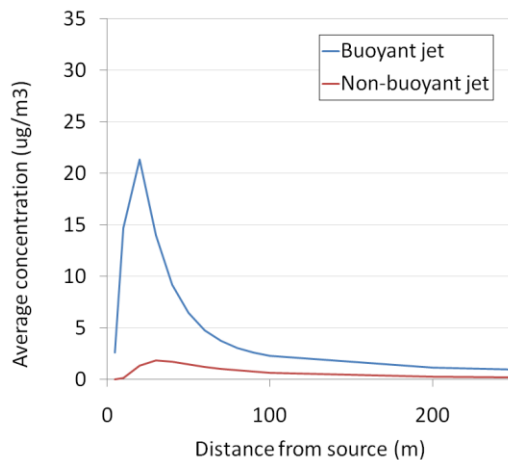
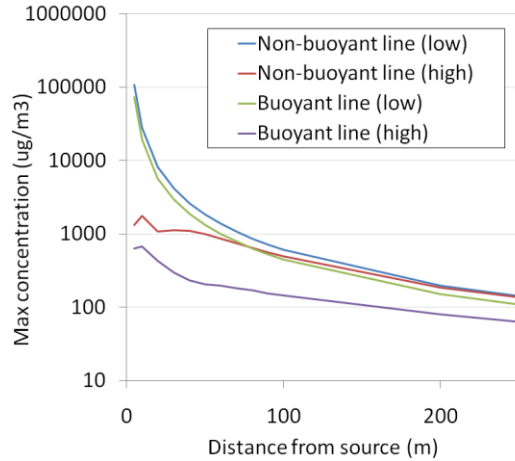
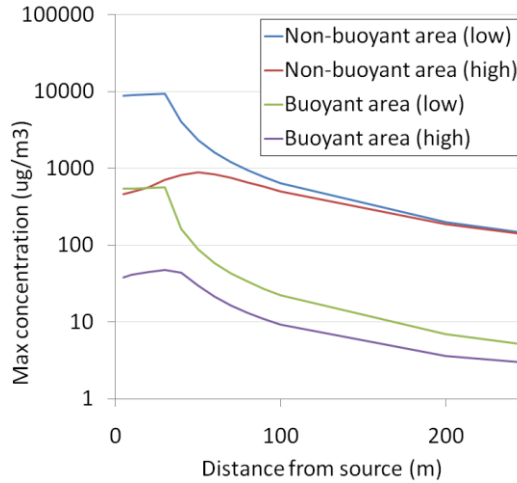


Figure 49 Annual average agricultural source results from ADMS and AERMOD; values are the average over each arc

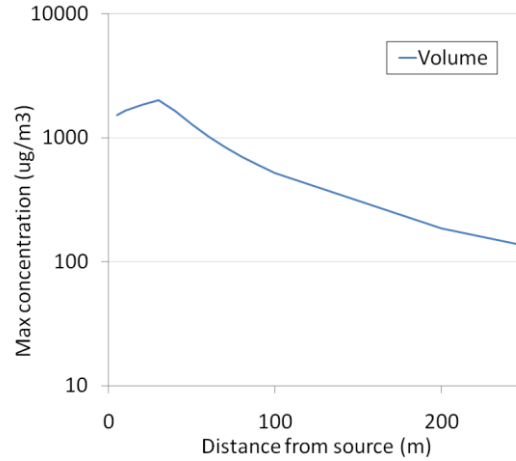
a) ADMS line source (agricultural sources)



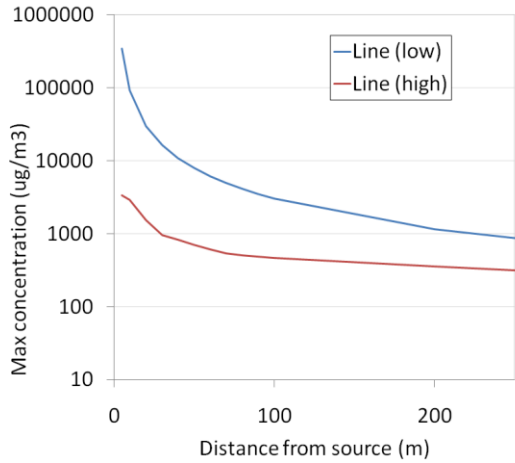
b) ADMS area source (agricultural sources)



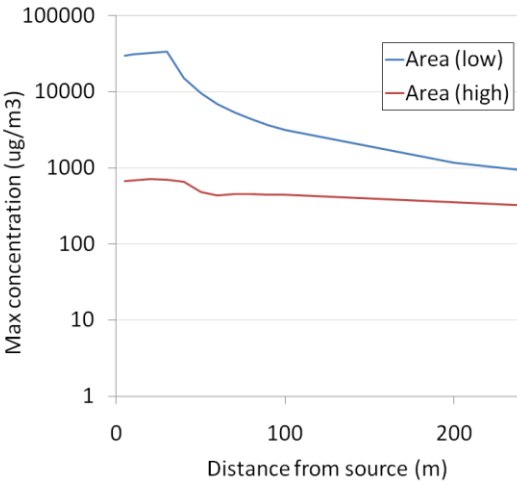
c) ADMS volume source (agricultural sources)



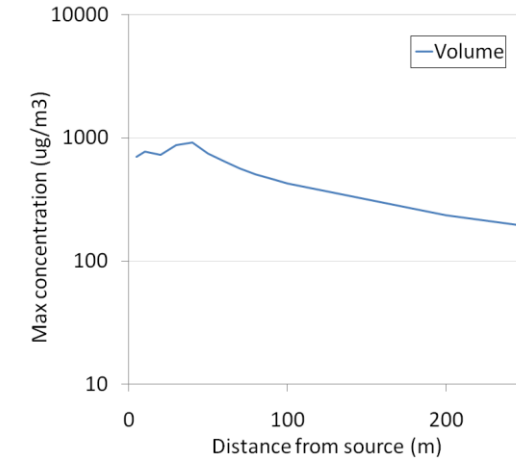
d) AERMOD line source (agricultural sources)



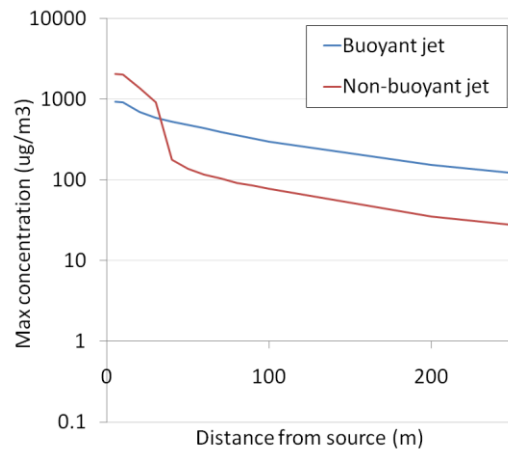
e) AERMOD area source (agricultural sources)



f) AERMOD volume source (agricultural sources)



g) ADMS jet source (agricultural sources)



h) AERMOD jet source (agricultural sources)

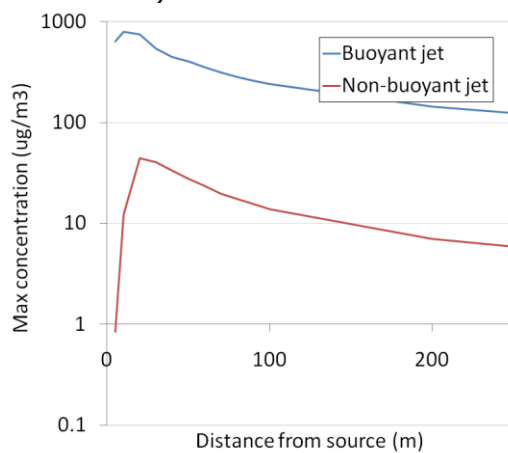


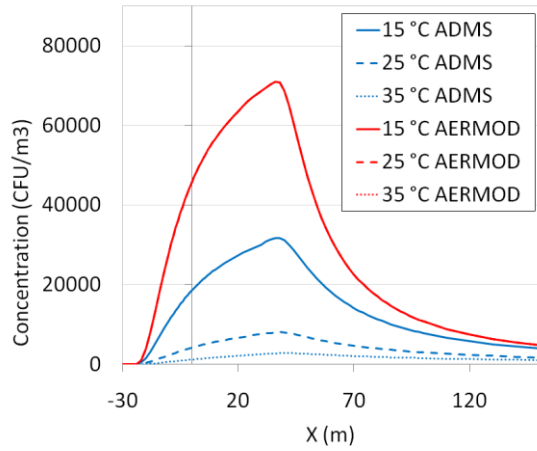
Figure 50 Annual maximum agricultural source results from ADMS and AERMOD; values are the maximum over each arc

D2 Bioaerosol source types

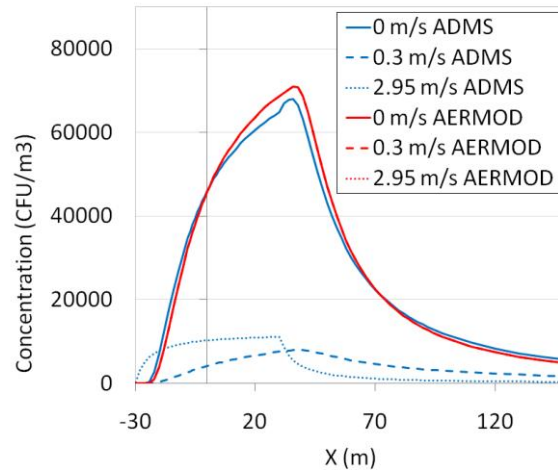
Section D2.1 presents the results for single meteorological conditions and Section D2.2 presents the annual average results.

D2.1 Single meteorological conditions

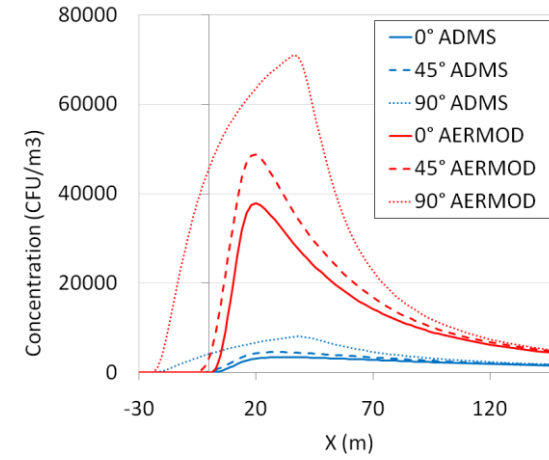
a) Varying exit temperature



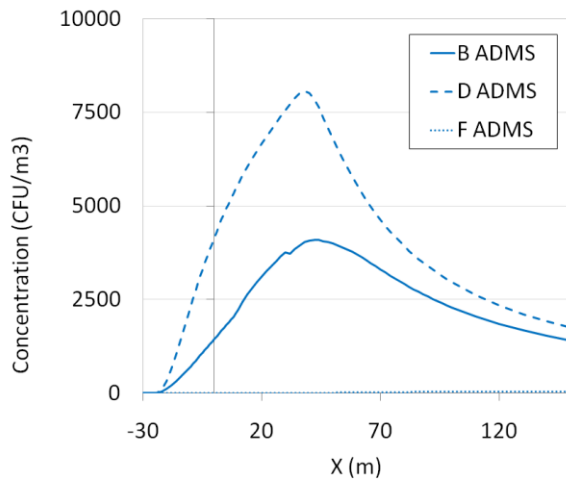
b) Varying exit velocity



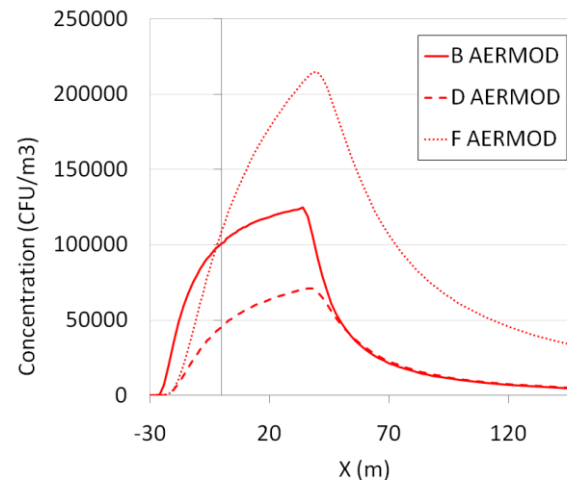
c) Varying orientation



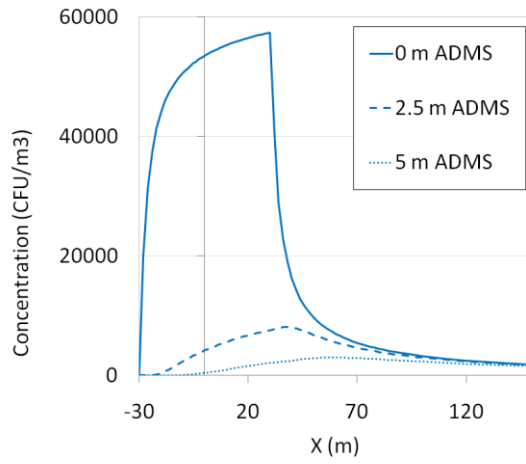
d) ADMS results with varying meteorological conditions



e) AERMOD results with varying meteorological conditions



f) ADMS results with varying height



g) AERMOD results with varying height

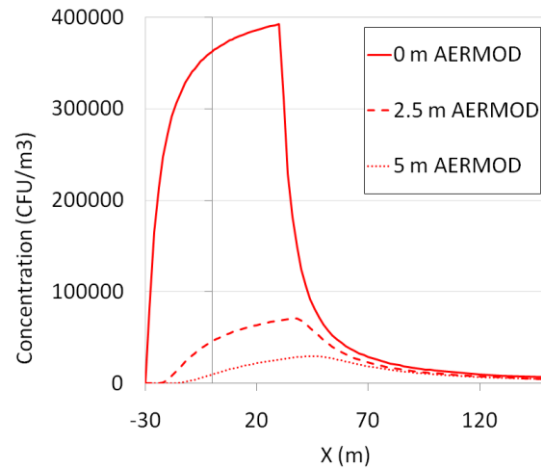


Figure 51 Bioaerosol area source results from ADMS and AERMOD

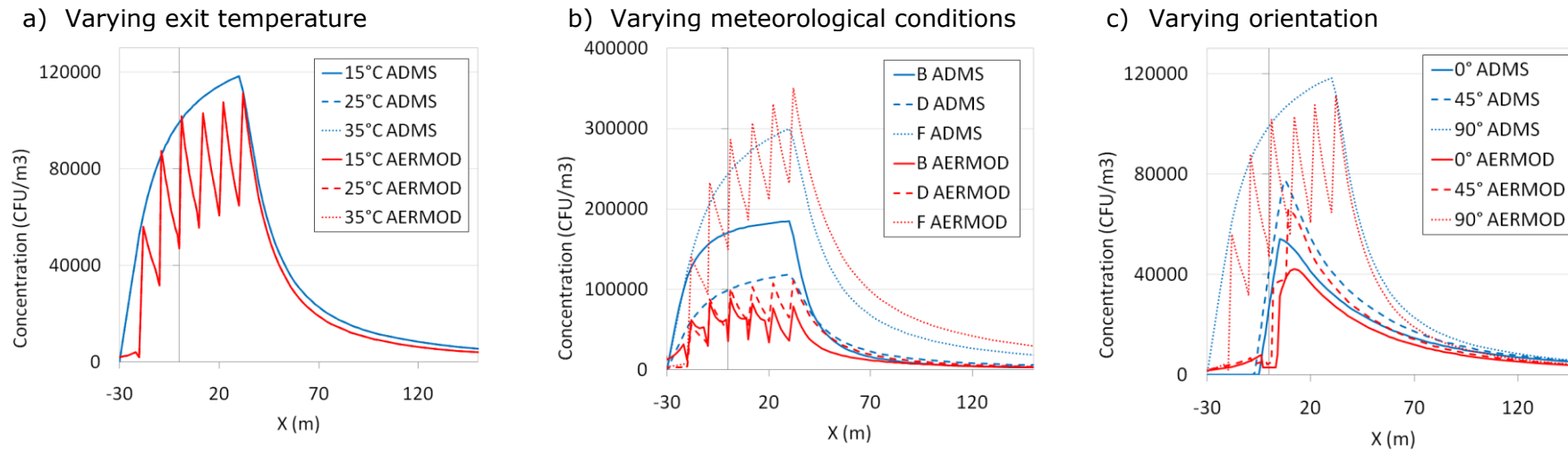
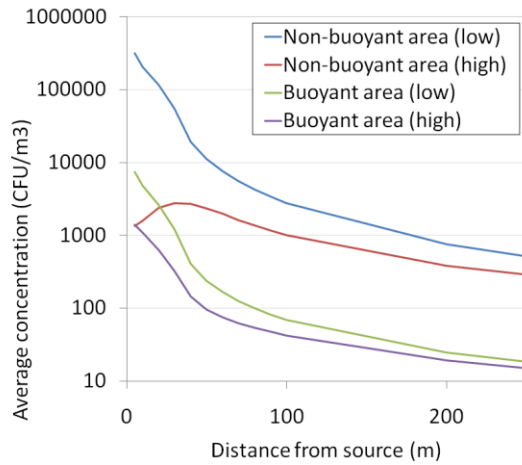


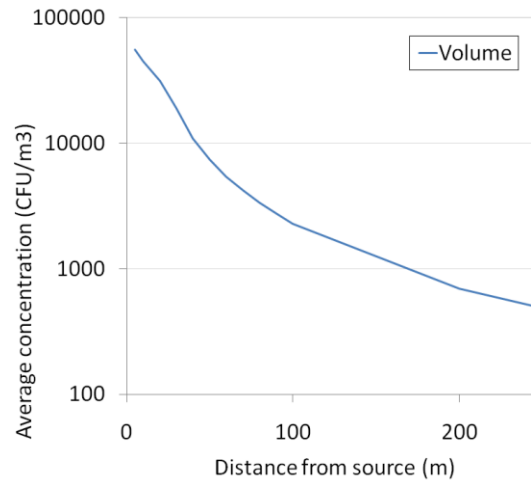
Figure 52 Bioaerosol volume source results from ADMS and AERMOD

D2.2 Annual averages

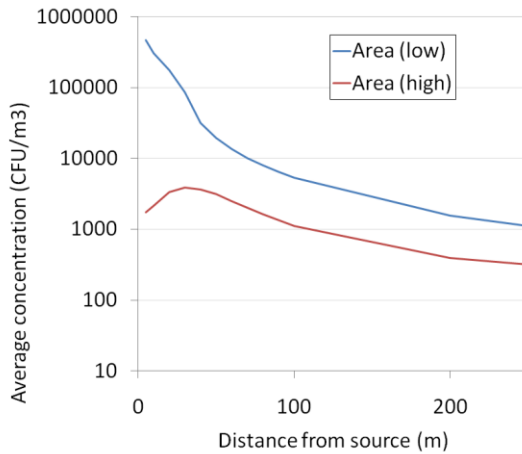
a) ADMS area source (bioaerosol sources)



b) ADMS volume source (bioaerosol sources)



c) AERMOD area source (bioaerosol sources)



d) AERMOD volume source (bioaerosol sources)

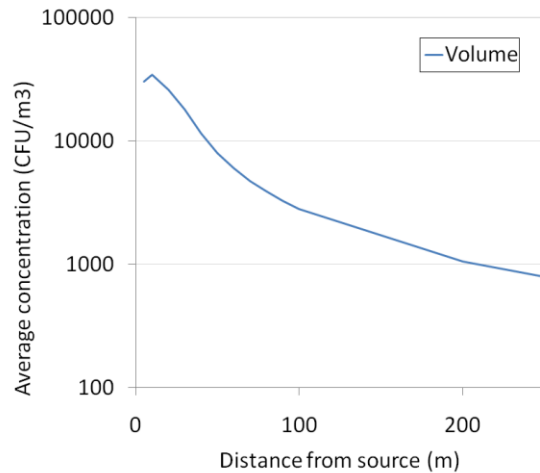
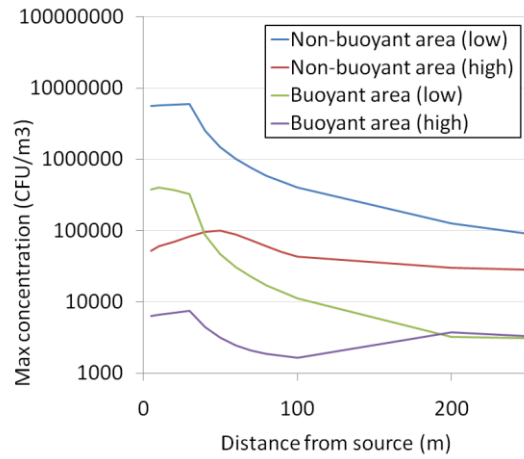
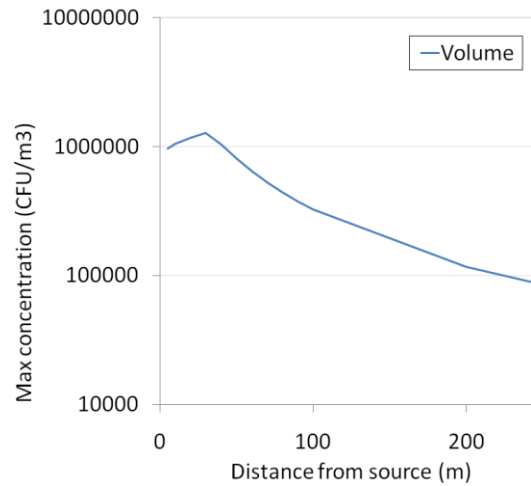


Figure 53 Annual average bioaerosol source results from ADMS and AERMOD; values are the average over each arc

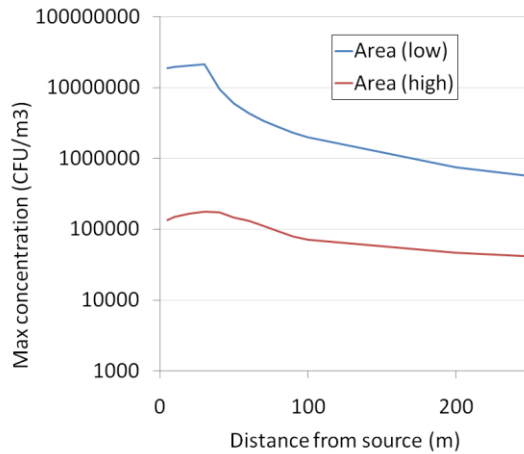
a) ADMS area source (bioaerosol sources)



b) ADMS volume source (bioaerosol sources)



c) AERMOD area source (bioaerosol sources)



d) AERMOD volume source (bioaerosol sources)

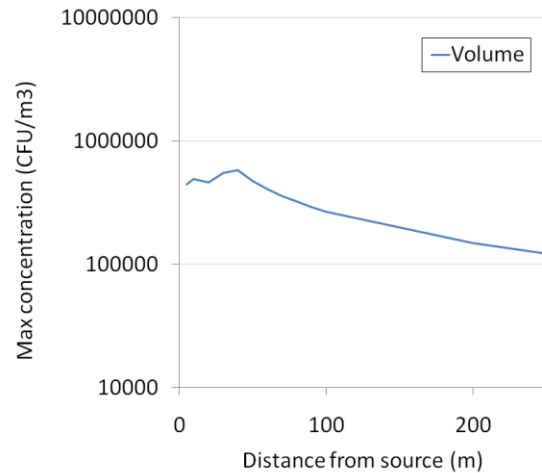


Figure 54 Annual average bioaerosol source results from ADMS and AERMOD; values are the maximum over each arc

APPENDIX E

The ISC3 User Guide (ISC3, 1995) details how buoyancy and momentum fluxes are calculated. The Briggs buoyancy flux parameter F_b (m^4/s^3) is calculated as:

$$F_b = g v_s d_s^2 \left(\frac{\Delta T}{4 T_s} \right),$$

where $\Delta T = T_s - T_a$, T_s is stack gas temperature (K), T_a is ambient air temperature (K), d_s is stack diameter (m), v_s is exit velocity (m/s) and g is acceleration due to gravity (m/s^2).

The momentum flux parameter F_m (m^4/s^2) is calculated as:

$$F_m = v_s^2 d_s^2 \frac{T_a}{4 T_s}.$$

In order to calculate whether buoyancy or momentum dominate plume rise, a crossover temperature is calculated. This is defined below.

- In neutral or unstable conditions, the crossover temperature $(\Delta T)_c$ is calculated as follows:

For $F_b < 55$:

$$(\Delta T)_c = 0.0297 T_s \frac{v_s^{1/3}}{d_s^{2/3}}$$

For $F_b \sim 55$:

$$(\Delta T)_c = 0.00575 T_s \frac{v_s^{2/3}}{d_s^{1/3}}$$

- In stable conditions, a stability parameter s is calculated:

$$s = g \frac{\partial \theta / \partial z}{T_a}$$

where $\partial \theta / \partial z$ is approximated as 0.020 K/m for Pasquill-Gifford stability category E and 0.035 K/m for stability category F. The crossover temperature is then calculated as:

$$(\Delta T)_c = 0.019582 T_s v_s \sqrt{s}$$

If the difference between stack gas and ambient temperature ΔT exceeds or equals $(\Delta T)_c$, the resultant plume rise is assumed to be buoyancy dominated, otherwise the plume rise is assumed to be momentum dominated.

APPENDIX F

This appendix presents the long-term ammonia average concentrations comparisons between the measurements taken at the Alpha Samplers and the modelled contour values. ADMS results for jet and volume sources, and AERMOD results for point and volume sources for the second run are shown in Section 4.2.4.2. The remaining results for this run are presented in this appendix i.e. point, line and area sources for ADMS (Figures 55 and 56) and line and area sources for AERMOD (Figure 57).

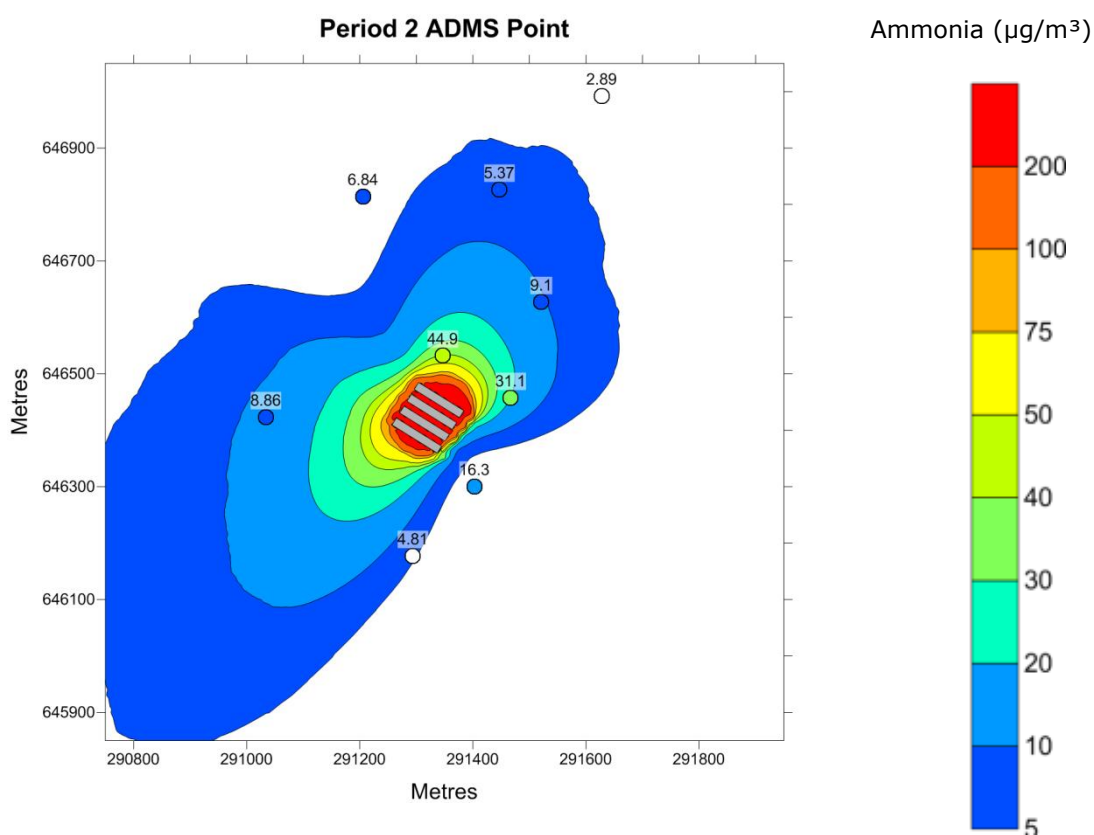


Figure 55 Period ADMS ammonia results for Whitelees for 'Run 2' when modelling using point sources. Observations shown by the circles, model results shown by the contour; all plots use same colour scale and the buildings are shown in grey.

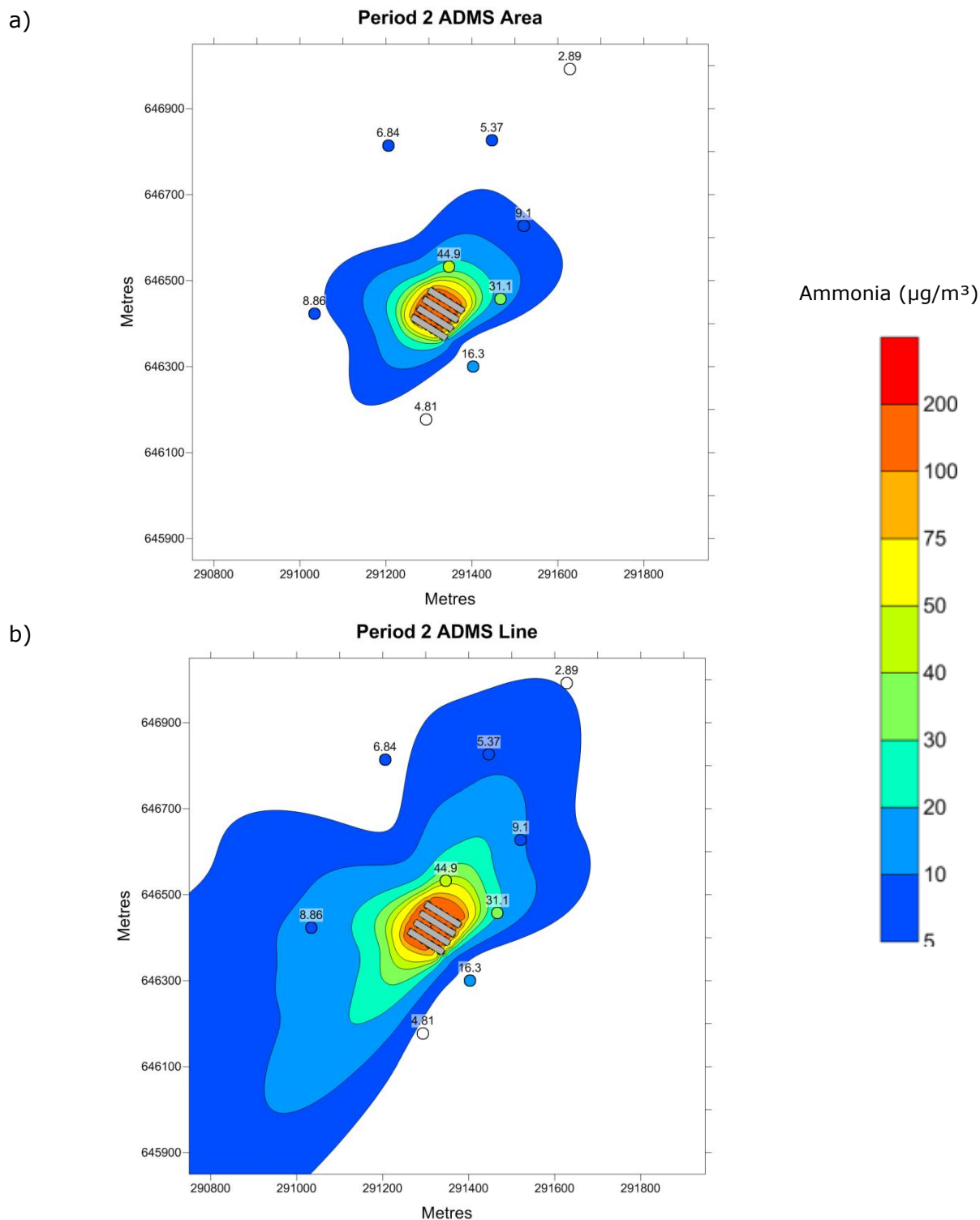
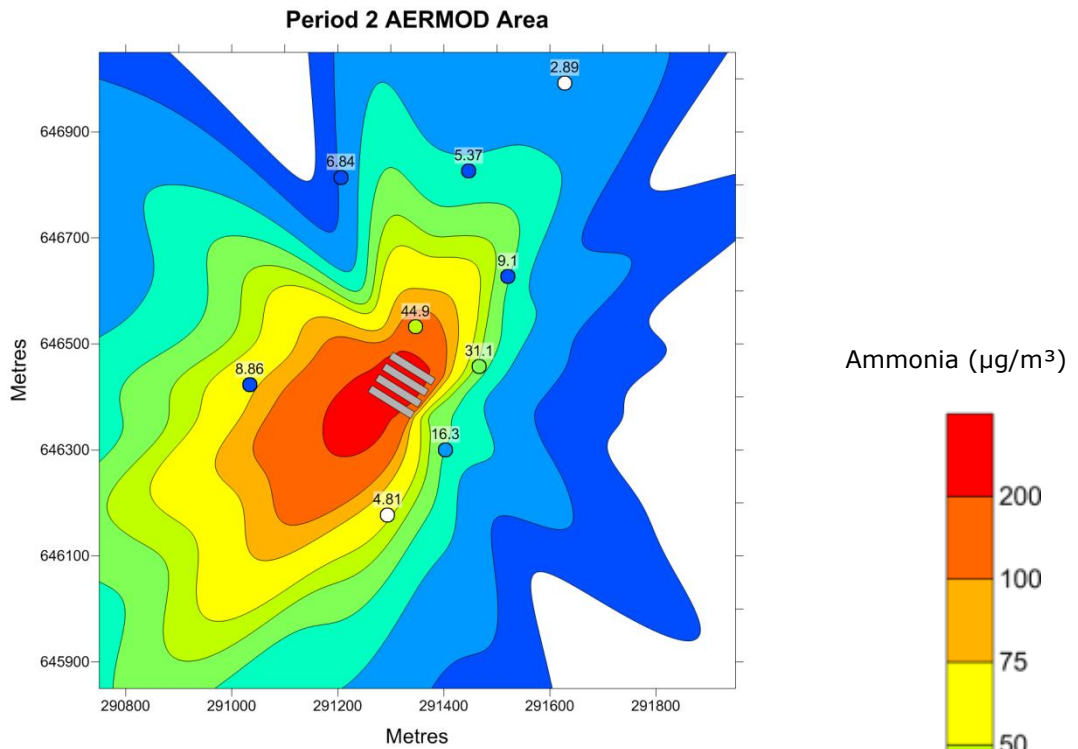


Figure 56 Period ADMS ammonia results for Whitelees for 'Run 2' when modelling using a) area and b) line sources. Observations shown by the circles, model results shown by the contour; all plots use same colour scale and the buildings are shown in grey (not modelled explicitly).

a)



b)

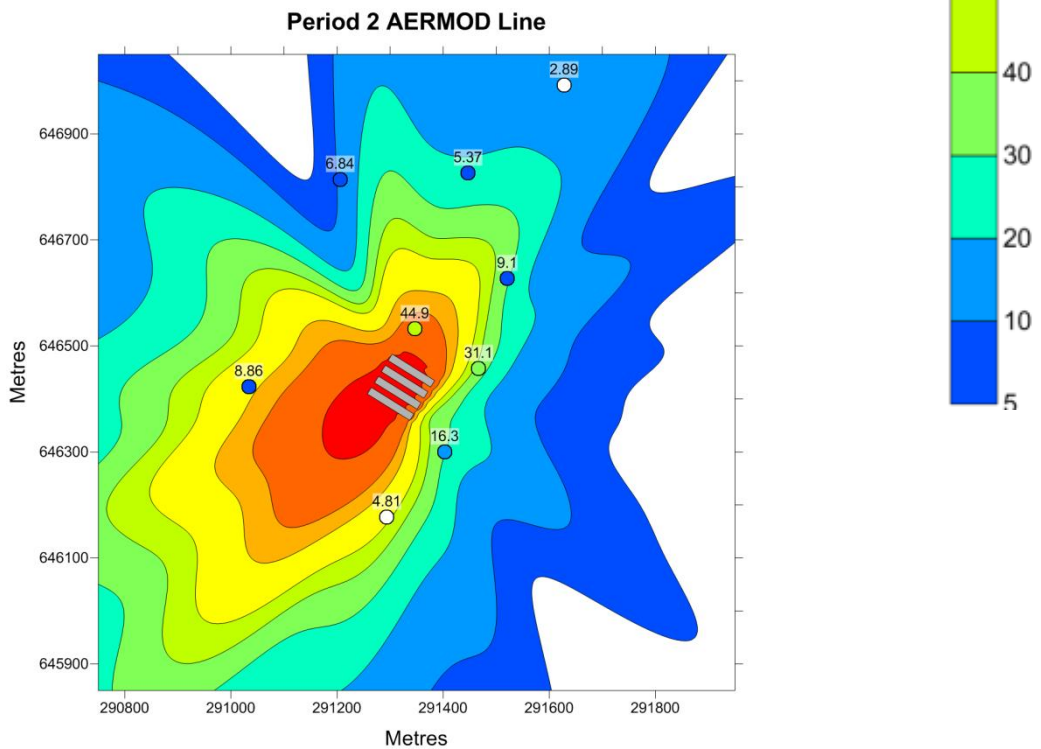


Figure 57 Period AERMOD ammonia results for Whitelees for 'Run 2' when modelling using a) area and b) line sources. Observations shown by the circles, model results shown by the contour; all plots use same colour scale and the buildings are shown in grey (not modelled explicitly).