Analysis of trace-gas changes following the 2001 outbreak of Foot & Mouth Disease: A case study to reduce the uncertainties in agricultural emissions abatement

Appendix to the Final Report to
Department for Environment, Food and Rural Affairs
Project AM0118
(Detailed report)


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April 2005
Client: Defra

Client Project number: AM0118
CEH Project number: C01941

Project Title: Monitoring & modelling trace-gas changes following the 2001 outbreak of Foot & Mouth Disease to reduce the uncertainties in agricultural emissions abatement.

Project start date: January 2002
Completion date: September 2004

Client Project Officer: P. Goodliffe
CEH Project Officer: M.A. Sutton


Report approved for release by: J.N. Cape

Reporting period: January 2002-September 2004

Report date: 12 April 2005

Report Number: AS 05/05

Report Status: Final report

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SUMMARY

1. This project established a network of sampling points within two study areas to monitor concentrations of NH₃, CH₄ and N₂O following the 2001 outbreak of Foot and Mouth Disease (FMD). The study areas are centred on Cumbria (extending into neighbouring counties and Scotland) and Devon (extending into Cornwall and Somerset), each consisting of 20 monitoring sites with around 15 in areas most affected by FMD and the remainder in areas little affected by FMD.

2. The prime aim of the project is to use the restocking of animals following FMD as a case study of changing emissions, to establish the relationship between livestock numbers, ammonia emissions and atmospheric NH₃ concentrations. If this can be done, then this increases the confidence in atmospheric model estimates that underpin the setting of NH₃ emission abatement targets. Atmospheric reactions with NH₃ are a major uncertainty, and therefore the monitoring also included CH₄ and N₂O as inert atmospheric tracers, to examine the potential cause of any discrepancies to model expectations.

3. This project follows on from an initial modelling study (AM0116, Sutton et al. 2004b) that mapped the location and extent of the expected changes. The initial project also assessed the likelihood that the expected changes would be measurable (given sampling detection limits) and attributable (given natural variability). It was concluded that the expected changes in NH₃ and CH₄ would be measurable and attributable, but that the uncertainties were likely to be larger for N₂O.

4. The present project established the new network very rapidly, in order that the effects of restocking could be monitored, as restocking had already started. This required deployment of a large and coordinated team of staff, but was successfully accomplished within one month of the project start date.

5. All sites in the network were visited on a monthly basis for two years, allowing equipment performance to be assessed regularly. This is important, since the required speed of establishing the network meant that battery operated, instead of mains-powered sampling had to be used for N₂O and CH₄ for the first time. The network has provided an important opportunity to refine the sampling methods, and complements activities under the DEFRA (LMID) MANE project and the DEFRA (AEQ) National Ammonia Monitoring Network (NAMN).

6. For the two study areas centred on Cumbria and Devon, the sites most affected by FMD have been compared with sites that were little affected. The measurements show substantial seasonal and inter-site variability in concentrations of each of the measured trace gases. This highlights the need for the multi-site assessment implemented in this study, comparing FMD-affected areas and areas not directly affected by FMD (“unaffected areas”). Data are presented here as graphs for the full two years of the measurement effort. The key observations are:

   a. Measured ammonia concentrations were reduced by around 25-35% in Cumbria and by around 15-20% in Devon in the FMD affected areas compared with unaffected areas during spring/summer 2002. This is consistent with the model predictions under the initial modelling project (AM0116). The second year of monitoring provided the necessary check to ensure that this was not an artefact of normal seasonal differences. The results showed some seasonal effect (i.e. part of the apparent reduction in NH₃ concentrations after FMD is an artefact resulting from different average seasonal cycles in the affected vs unaffected areas), but this was much smaller than the changes observed,
demonstrating that the signal of changes in animal numbers following FMD was detected.

b. Methane concentrations showed substantial seasonal variation, with unexpected peak concentrations in spring and autumn. The seasonal differences were more pronounced for the Cumbria compared to the Devon sites. This may be due to emissions from manure spreading activities (being larger than previously thought) and further assessment is required. By contrast to NH$_3$, the observed reduction in CH$_4$ concentrations for FMD affected areas was very uncertain and less than that expected from the preliminary modelling (AM0116). Modelled CH$_4$ reductions in the worst affected areas were 25-60 ppb for Cumbria and 10-25 ppb for Devon. However, these changes were not reflected in the measured CH$_4$ concentrations, for which non-significant trends in the FMD affected areas relative to unaffected areas were detected.

c. Nitrous oxide concentrations showed a very strong seasonal variation, especially in Cumbria, both in FMD affected and non-affected areas. This implies a clear control of N$_2$O emissions by N fertiliser application, temperature and wetness. The preliminary model assessment for N$_2$O was recognized as being rather uncertain, but suggested that FMD would reduce N$_2$O concentrations by 0.3-0.7 ppb in the worst affected areas of Cumbria and by 0.1-0.2 ppb in the worst affected area of Devon. By contrast to this expectation, the results show higher concentrations (by 2-4 ppb) in the FMD affected areas for Spring 2002 for both Cumbria and Devon. These differences are expected to result from the complex interaction with soil conditions (e.g. fresh soil compaction in FMD affected areas and/or interannual variability), and point to the need for further assessment on the controls of N$_2$O emission. As an inert-tracer for the present experiment N$_2$O was therefore uncertain, and the modelling analysis focused on NH$_3$ and CH$_4$.

d. While it is well established that the NH$_3$ measurements are robust, the reliability of the CH$_4$ and N$_2$O measurements also needs to be addressed. Quality assurance and quality control (QA/QC) of the measurement and analysis of CH$_4$ and N$_2$O confirmed that the experimental errors are smaller than the measured differences in concentrations, so that the broad patterns are a result of real spatial / temporal differences in N$_2$O and CH$_4$ concentrations.

7. The results of the measurements are unexpected, as the initial assumption was that concentrations of CH$_4$ (being an inert tracer) would increase in proportion to emissions during restocking, while NH$_3$ might not change in proportion to emissions, because of non-linear atmospheric interactions. The very small observed changes that can be related to FMD for CH$_4$ (which was much less than expected) may be partly due to:

a. Rather rapid restocking, such that much of the change had already happened before the measurements started. Conversely, the clear effects seen for NH$_3$ lasted well into the measurement period and may result from the lag in NH$_3$ emissions due to land spreading emissions occurring some months after the excretion from the animals.

b. Unexpected interactions that affect CH$_4$ emissions (as indicated by the substantial seasonal variability), both due to climate and agricultural management effects, including local variability in CH$_4$ concentrations. Such effects are clearly indicated for N$_2$O (where emissions unexpectedly increased following FMD, as well as showing substantial seasonal variability).
c. There is a need for improved precision in the CH₄ measurements if such small changes are to be detected. For this purpose the benefits of replicate foil bag sampling should be tested in the field.

8. This study has shown that there is significant inter-annual and intra-annual variability in N₂O and CH₄ concentrations in agricultural source areas that is larger than in remote areas, such as Mace Head and Shetland. This has not been clearly demonstrated before, since the current monitoring data for N₂O and CH₄ are focused on a few remote sites. At present monitoring of these gases on an operational basis is restricted to remote locations to assess global background values. However, monitoring in source regions provides a means to integrate the effects of climate and management on emissions and identify unexpected effects on emissions. This highlights the need to establish a wider monitoring effort for N₂O and CH₄ that would allow the effects of agricultural and environmental policies (e.g. CAP reform, Kyoto compliance) on long-term emissions of these gases to be assessed.

9. In modelling the time course of restocking after FMD, this study has provided the first spatio-temporal modelling of UK ammonia and methane emissions at the monthly level. For this purpose data from the British Cattle Movement Society and the State Veterinary Service proved essential, together with estimation of the basic seasonal patterns in CH₄ and N₂O emissions. The comparison with the monthly measurements has highlighted limitations in the BBSRC National Ammonia Emissions Inventory (NAEI), and in particular demonstrated how manure spreading on frozen soils in winter is a more widespread activity than currently included in the Inventory.

10. The detection of the change in NH₃ emissions in the measurements for both the Cumbria and Devon study areas is a major achievement, particularly given the short duration of this study. It shows that:
   a. The problems of the “ammonia gap” in the Netherlands are not necessarily due to a decoupling between ammonia emissions and air concentrations in source areas. The most likely explanation of the ammonia gap at present is normal limitations in atmospheric models and the limited time extent of data series.
   b. The question of the ammonia gap in the Netherlands remains somewhat different to the present study, since this followed mean concentrations over several years, with parallel changes in SO₂ and NOₓ emissions, causing additional complexity.
   c. The design of the present sampling network allowed greater power to distinguish the FMD signal in NH₃ by comparing FMD affected and unaffected areas. While the trend in average NH₃ concentrations in FMD affected areas was not significant (due to short term variability), the data normalization and referencing to unaffected sites allowed most of the short term variability to be factored out. By using this approach it was possible to show clear reductions in NH₃ concentrations in affected areas and increases that parallel the modelled changes on restocking.
   d. In both Cumbria and Devon, the measured changes in NH₃ concentration were larger than the modelled changes (although not significantly so). If this is a real feature, the cause of it is not clear, but may reflect other factors that were not fully taken account of in the modelling, such as how ammonia emissions may initially be lower per animal on restocking as the capacity of the plant/soil system to absorb ammonia becomes increasingly saturated.

11. The comparison of modelled and measured changes in CH₄ concentrations proved an extremely useful exercise to test this as an inert tracer of NH₃ emissions. In future studies special attention should be given to:
a. Assessing the local (landscape level) variability in CH\(_4\) concentrations in agricultural areas. This has not been quantified before, and may have been a significant cause for variation in the measurements, depending on distance to nearby agricultural and non-agricultural sources.

b. Include nearby background reference sites for CH\(_4\) measurement. Although remote measuring stations such as Shetland provide a good basis to assess global background values, additional uncertainties are introduced by these sites being very remote from the study areas (with possibly different values). Therefore, it would be of increased value to include nearby “regional background sites”. Although these may still be affected to some extent by local emissions, this may be factored out by comparison with modelling, as it is the difference in signal, which is most critical. For example, in the present study it would have been desirable to include high altitude reference sites in the Cumbrian mountains and Dartmoor.

c. Improving the sampling precision of the foil bag-TDL approach. Although replicability was shown to be excellent in laboratory tests, there was a clear difference in data quality for the CH\(_4\) measurements between the Cumbria and Devon study areas. This suggests that further attention is needed to improve data capture and sampling methods. In particular, replicate sampling should be tested in the field over longer periods as standard to demonstrate the robustness of each measurement point and allow improved data screening.

12. The results of the present study show that NH\(_3\) emissions did increase as expected following FMD and that this was detectable by a monitoring network of multiple sites comparing affected and unaffected areas. This study therefore supports the benefit of reducing ammonia emissions in abatement strategies, as the outcomes in terms of reduced concentrations are found to be detectable. However, it must be recognized that such a rapid detection of change as was demonstrated in this study is only possible were emissions reductions in some areas can be contrasted with nearby areas where reductions are not made. In the case where reductions in emissions are widespread (e.g. country wide), much longer periods of monitoring (e.g. >5-8 years) are necessary to detect typical trends of the same magnitude.
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1. INTRODUCTION

This project has monitored trace gas concentrations following the restocking of animals after the 2001 outbreak of Foot and Mouth Disease (FMD) and compared these with model estimates. Ammonia (NH₃) and methane (CH₄) have provided the main focus, with these gases being monitored at 20 sites each in and surrounding two areas substantially affected by FMD (Cumbria and Devon).

The initial policy interest was primarily focused on NH₃. This is because of concerns regarding the uncertainty in the emissions abatement potential: in several European countries estimated NH₃ emission reductions were not accompanied by clear decreases in reduced nitrogen (NH₄⁺) concentrations and deposition (Sutton et al. 2003). This raised the questions of:

a) whether NH₃ emissions abatement measures are as successful as previously thought, and

b) whether there are atmospheric uncertainties that mask the link between changed emissions and the consequent responses in atmospheric concentrations and deposition (given that some examples concerned changes in animal numbers rather than implementation of abatement policies).

Ammonia is a reactive gas and this leads to several uncertainties in its atmospheric behaviour. For example, it is readily scavenged by precipitation, leading to wet deposition (NEGTAP 2001), as well as absorbed differently by various land/plant community types through dry deposition (e.g. Sutton et al. 1993, DEFRA 2002). Ammonia also reacts with atmospheric acids to form aerosols containing ammonium (NH₄⁺). As a result, the decrease in SO₂ and NOₓ emissions over recent years (NEGTAP 2001) might be expected to lead to a change in partitioning between NH₃ and NH₄⁺. Hence, NH₄⁺ aerosol concentrations may decrease at the same time as NH₃ concentrations increase, even if the emissions of NH₃ remain unchanged (Sutton et al. 2004a).

In order to consider these interactions, the present project set out also to evaluate the changes in CH₄ concentrations after the FMD outbreak, since CH₄ is effectively an inert tracer in the atmosphere (on the relevant timescales of regional-scale dispersion away from sources). Methane is not scavenged by wet deposition, while its dry deposition rates, through methane oxidation in soils, have an insignificant effect on CH₄ concentrations in source areas. Since the emissions of both NH₃ and CH₄ are dominated by livestock sources in the rural areas affected by FMD, both gases might be expected to see parallel changes following the restocking after FMD. A possible caveat for CH₄ is the contribution of gas leaks and landfill to CH₄ emissions in rural areas. However, this depends on the nearness to specific localized sources, which are more discrete in location than livestock. The CEH AENEID (Atmospheric Emissions for National Environmental Impacts Determination) model provides spatial estimates of the distribution of NH₃ and CH₄, particularly focussing on agricultural sources (Dragosits et al. 1998; Sozanska et al. 2001, Sutton et al. 1996, Beswick et al. 1999) and has recently been extended to improve the distribution of CH₄ from all sources. Outputs from this model are also now being used as part of delivery of the National Ammonia Emissions Inventory (NAEI). From the AENEID results, it is therefore possible to map the distribution of dominant sources for both NH₃ and CH₄. Figures 1 and 2 show that in both Cumbria and Devon, total NH₃ and CH₄ emissions are dominated by livestock sources (mainly cattle), and therefore parallel reductions during FMD may be expected.

In order to implement the sampling procedure for the project, time-integrated monthly samples were collected. CEH ALPHA samplers were used for NH₃ measurements. Collection of air into foil bags, with subsequent analysis by tunable diode laser absorption spectroscopy (TDLAS) at CEH Edinburgh, was used for the CH₄ and N₂O measurements.
In an initial feasibility study for the present project (AM0116, Sutton et al. 2002, 2004b), consideration was also given to the expected changes in N₂O emissions following FMD. Because of the close link to soil processes acting on longer timescales, it was concluded that the quantitative link between N₂O and CH₄ / NH₃ emissions following FMD would be much more uncertain. Given resource limitations, it was therefore agreed to focus the comparison of measurements with modelling on CH₄ and NH₃. However, although N₂O was not included in the present project, the bag samples were also analysed for N₂O, with a modest additional effort. The additional N₂O dataset thus collected provide an additional resource for potential assessment in the future. These N₂O samples have given additional information relevant to the DEFRA MANE project, which has established a preliminary national network for N₂O monitoring across the UK as an alternative approach to estimating N₂O emissions.

At the same time, in addition to the measurements contracted to DEFRA under MANE, CEH has undertaken at its own cost CH₄ analysis of the air samples at the National Nitrous Oxide Network sites. These measurements have the benefit of providing added information on CH₄ concentrations in areas NOT affected by FMD for comparison with the measurements in the present project.

Figure 1: Spatial distribution of the dominant sources of atmospheric ammonia emission as derived from the AENEID model (Dragosits 1999; Sutton et al. 2001).
The following sections detail the measurements and modelling undertaken to examine the coupling between changes in NH$_3$ and CH$_4$ following the course of animal restocking after FMD. For this purpose, where available and relevant, the comparison includes measurements made both for this project as well as measurements from the National Ammonia Monitoring Network (NAMN) and additional CEH measurements of CH$_4$ at other sites. The results are then discussed in relation to the scientific uncertainties of ammonia abatement policies.

2. OBJECTIVES

The overall task was to analyse the effect of the changes following FMD to reduce uncertainties in the link between agricultural trace gas emissions and concentrations in the atmosphere. This includes the following specific objectives:

1. To establish methods for monthly monitoring of CH$_4$ and NH$_3$ in two case study areas and to prepare samples for each month.

2. To establish monitoring sites in Cumbria and Devon to sample NH$_3$ and CH$_4$ on a monthly basis through 2002 and 2003. Given the spatial variability, each area had 20 sites, with most in the core affected area and some in nearby unaffected areas. The measurements were established with urgency through intensive staff deployment.
3. To use CEH ALPHA samplers (as used in the UK National Ammonia Monitoring Network or NAMN) for measuring NH₃ and bag sampling with Tunable Diode Laser Absorption Spectroscopy analysis for CH₄ measuring. The TDL was also applied to measure N₂O in the collected samples.

4. To combine data on animal numbers slaughtered associated with the FMD outbreak with information for the Cumbria and Devon study areas on the timescales of restocking, in order to estimate the spatio-temporal changes in animal numbers in the case study areas.

5. To combine the detailed monthly livestock numbers for the study areas with the Agricultural Census data and modified agricultural practices in the light of FMD, as well as normal seasonal differences in emissions to estimate the temporal course (on a monthly level) of NH₃ and CH₄ emissions and to map these emissions over the UK.

6. To utilize the spatio-temporal emission data to run the UK-scale FRAME model to estimate the effect of FMD on NH₃ and CH₄, providing maps of the concentrations and changes through 2002-2003.

7. To analyse the spatial and temporal patterns of monitored and modelled NH₃ and CH₄ concentrations, to investigate the extent to which the modelling is able to reproduce the expected changes due to restocking following FMD, and to report on the state of our understanding on the links between emissions, concentrations and deposition.

3. METHODOLOGY

3.1. Work Package 1: Establishment of monitoring methods and sample preparation (CEH)

The measurement methods were established and implemented as planned. This was an extremely challenging target, bearing in mind the need to build substantial amounts of sampling equipment (especially for CH₄) and to have it operational quickly (within 1 month) in order to sample the gases before animal re-stocking occurred. While the CEH ALPHA samplers have performed well throughout, the CH₄ sampling involved setting up battery-powered sampling sites, using a new design pump and air constriction system. Problems that occurred in setting up included failure of the air pumps, blockages in the micro-bore air tubes and occasional water ingress removing the aluminium coating of the foil bags and leakage of foil bags. Any affected balloons were therefore replaced the following month.

Tests were made to investigate the stability of CH₄ collected in the foil balloons. On two separate occasions sets of 20 balloons were filled with standard gas concentrations (1890 ppb CH₄ and 305 ppb N₂O). After one month of storage, CH₄ and N₂O concentrations deviated from a ‘fresh’ standard by 0.5% and 0.65%, respectively. These results show that diffusion and leakage into and out of the balloons was sufficiently small and did not mask any spatial and temporal variability between sites.

In order to overcome the limited lifetime of the air pumps and the electrical capacity of the heavy duty batteries used, a new electrical circuit was designed with a timer, whereby CH₄ is only sampled for one minute every 16 minutes. This reduces the required electric current and allows a faster airflow during sampling (which enables an air-constrictor with a larger diameter bore to be used, reducing the chance of blockages), while at the same time permitting effectively continuous air sampling throughout the monthly sampling period. Tests comparing this approach with continuous sampling showed no detectable differences.
3.2. Work Package 2: Establishment of monitoring sites and sample exchange (CEH, IGER)

In parallel with the development and building of the sampling systems, staff from both CEH and IGER identified the most suitable field locations in each study area, using local maps of the percentage change in air concentrations of NH$_3$ and CH$_4$ expected from the preliminary study (AM0116, Sutton et al. 2002, 2004b) and an indicative distribution of sites overlaid onto a 5 km grid resolution map.

Site selection criteria included:

- Ensuring that most sites are in worst affected areas (e.g. 15 out of 20 per study area)(16 in Cumbria)
- Establishing some sites in unaffected surroundings (e.g. 5 per study area)(4 for Cumbria). (These points have been supplemented by existing national monitoring sites either in the vicinity or further away by the National Ammonia Monitoring Network (NAMN) or by CEH activities complementing the MANE project).
- Including a maximum of one sampling point per 5 km x 5 km grid square
- Avoiding sampling under trees and ensuring a good airflow around sampling points, and with sites avoiding hollows and depressions.
- Avoiding sampling in the immediate vicinity of farmyards and manure piles (<100 m), in order to sample average rural concentrations rather than have a dominant influence of one local source.

Suitable sites included private gardens, post offices, wildlife trusts, golf courses, school grounds etc. Once all the potential sites were identified, teams from CEH and IGER installed the equipment. At each site, samples were taken at 1.5 m above ground level over short vegetation, and photographs of each site taken, together with notes on the occurrence of livestock in the vicinity. (It should be noted that sites were established in winter, which made it difficult to estimate the height which summer vegetation would reach. Consequently, some sites were affected by tall grass/herbs during the summer months. In such cases a circle of vegetation, of one to two metres diameter, was flattened during the monthly visits to the site, and extra photos were taken at these times.) Following the initial set-up period, staff of CEH and IGER serviced the sites and changed-over samples on a monthly basis. At some sites vandalism of samples was a problem, although the losses of samples are smaller than those due to sampling malfunction (for the CH$_4$ sampling only).

The resulting sampling networks that were established centred on Cumbria and Devon are shown in Figures 3 and 4, overlaid on the preliminary estimates of reductions in NH$_3$ concentrations according to Sutton et al. (2002, AM0116).
Figure 3: Names and locations of the monitoring sites for NH₃, CH₄ and N₂O established in the present project for the area centred on Cumbria. Sites shown in red are the existing nearby sites for NH₃ sampling under the National Ammonia Monitoring Network. The background map shows the anticipated % reduction in NH₃ concentrations after FMD as modelled under project AM0116 (Sutton et al. 2002).
Figure 4: Names and locations of the monitoring sites for NH₃, CH₄ and N₂O established in the present project for the area centred on Devon. Sites shown in red are existing nearby sites for NH₃ sampling under the National Ammonia Monitoring Network. The background map shows the anticipated % reduction in NH₃ concentrations after FMD as modelled under project AM0116 (Sutton et al. 2002).

3.3. Work Package 3: Chemical analysis of gas concentrations (CEH)

The monthly samples from Cumbria and Devon were returned to the CEH Edinburgh laboratory for chemical analysis. The ALPHA samplers for NH₃ were analyzed in accordance with procedures developed for ammonia measurements in the National Ammonia Monitoring Network (Sutton et al. 2001), to ensure full consistency of protocols. The analytical procedure for the measurement of ammonium in aqueous extract from the ALPHA samplers uses the sensitive automated AMFIA (AMmonia Flow Injection Analysis) system, which operates on the principle of membrane dialysis, followed by measurement of conductivity.

For the foil bag samples, CH₄ and N₂O were analyzed on the CEH Tunable Diode Laser. Again, to ensure full consistency, the measurements were conducted in parallel with the monthly samples for the DEFRA MANE project. (The national measurements of N₂O at 33 sites under MANE were continued until April 2003). Measurements were then continued at a skeleton of 13 sites until January 2004 in order to maintain a link between the present project and a separate DEFRA project monitoring CH₄ concentrations to assess emissions from mines). Based on the laboratory analysis, exposure periods and calibrations, the data were analyzed to calculate monthly air concentrations of NH₃, CH₄ and N₂O for each site.
3.4. Work Package 4: Assessment of monthly animal numbers at parish level (IGER, CEH)

The total numbers of animals slaughtered due to FMD were already available from the initial project (AM0116, Sutton et al. 2002) across the UK and have been integrated to provide 5 km maps of emissions. However, to analyse the measured concentrations it is necessary to establish the time-course of restocking in the case study areas. Apart from the relevant differences over time, the overall change over the restocking period may also have been different from the change occurring at the onset of the FMD outbreak. Obtaining the monthly livestock numbers was a major data compilation activity, which drew on information from the animal movement licenses and the cattle passport scheme. As the measurements and modelling were conducted at a monthly level, the data on animal movements were summarized to the same frequency. Given the obvious scale of this task, it was restricted to the areas of the Cumbria and Devon case studies.

Based on the DEFRA FMD statistics, there were 173 cases (by farm holding) of FMD in Devon (the last identified on 17/06/01) and 893 cases in Cumbria (the last identified on 30/09/01). Re-stocking obviously began some time after the final FMD cases were identified in each of the study areas and the objective of WP4 was to provide the best estimate of monthly livestock numbers (distinguishing the livestock categories used in the ammonia emissions inventory), from January 2002, which could be used to generate monthly emission data for the 2 study areas.

A number of potential sources of data were identified and investigated:

- June agricultural census
- Local Trading Standards Offices
- Animal Movement Licensing Scheme
- British Cattle Movement Society
- State veterinary service – restocking licences
- Local livestock markets
- Local abattoirs
- Expert opinion on lambing times and slaughter dates

**June agricultural census**

The census data for the years 2000-2003 give snapshots around which monthly estimates of livestock numbers can be fixed. Parish level census data (livestock numbers and crop areas) were obtained from Defra for England for 2000-2003. Data for Wales and Scotland necessary for the spatial emission and concentration modelling were obtained directly from the devolved authorities by CEH.

**Local Trading Standards Offices**

Local Trading Standards were initially responsible for issuing and collating livestock movement licences within the FMD restricted areas. Discussions with the appropriate bodies for Devon and Cumbria revealed that large volumes of paper-based records existed (>50,000 for Devon). These recorded movements within or out of the county, but not movements into the county from elsewhere. It was decided that it would be very difficult to obtain anything very useful from this data source.

**Animal Movement Licensing Scheme**

This centralised scheme took over the licensing and data collating form the local Trading Standards from September 2001. The scheme provided a figure for net movements of livestock into both Devon and Cumbria for a fixed period (September 2001 to November...
2002). However, the scheme was unable to provide data broken down by livestock type and sub-category, parish and month.

**British Cattle Movement Society**

The most important data source was the British Cattle Movement Society (BCMS), which, after some delay (leading to an overall delay in the project), was able to provide monthly data for cattle numbers for each parish within Devon and Cumbria, categorised by breed, sex and age. Cattle numbers were re-allocated to the categories used in the AENEID model, making some assumptions regarding breeds being either dairy or beef. Data were also supplied for counties surrounding the study areas in order to improve the emission estimates for these areas, given that measured and modelled concentrations within the study areas would be affected by adjacent emissions. Data were supplied to IGER for January 2002 to January 2004. In addition, county totals for the study areas and surrounding areas for all cattle were provided for each month of 2001.

The BCMS data available at Parish level were converted to AENEID animal categories, to enable mapping of emissions for the study areas and surrounding counties. For the rest of the UK, the June census provided annual fixed points and with the time course of restocking post-FMD in other areas applying averages based on the affected areas. This simplification would have had only a small effect on the modelled ground level concentration enhancements, since these are dominated by local sources.

**State Veterinary Service**

Restocking licenses were issued by the State Veterinary Service and recorded on a central database. This provided information on when farms were visited, to check whether they were fit for restocking, together with the numbers of livestock involved. However, the data only relate to controlled restocking. If farmers waited for a specified time period, they could restock without informing the State Veterinary Service. For Devon, the number of holdings visited for restocking was about half of the number on which animals were culled. Restocking visits were recorded according to county, parish and holding, with the number of livestock (by type) present at each visit also recorded. These data have been useful in identifying the period when restocking occurred.

**Local livestock markets, abattoirs and expert opinion**

Lambing is an event that is not recorded centrally in any way, so that changes in sheep demography and lamb numbers were therefore difficult to estimate reliably. It was thought that numbers of sheep and lambs moving through local markets and abattoirs might give an indication to both lambing times and numbers. However, it was concluded that price, rather than livestock age, would determine the time of marketing, making it difficult to use such data for determining lambing time. In addition, no data were forthcoming from local abattoirs. An expert on sheep farming (Kate Phillips, ADAS) was consulted to provide estimates of birth and slaughter dates for lambs in Devon and Cumbria.

**3.5. Work Package 5: Assessment of detailed temporal and spatial changes in emissions (IGER and CEH)**

The information on animal numbers and restocking was combined with the agricultural census data and information on agricultural practices to estimate the detailed temporal pattern of NH₃ and CH₄ emissions. The work was conducted to be consistent with the standard national inventories provided annually to Defra by IGER *et al.*). The seasonal estimates take on board information concerning the modification of management practices following FMD (e.g. differences in manure storage practices), as well as normal seasonal differences in practice.
The work investigated time-lag effects between re-stocking and emissions for NH$_3$ and CH$_4$. In the case of CH$_4$, as the agricultural emission is dominated by eructation, the emission is closely coupled with the presence of animals, so that emissions should directly follow restocking. By contrast, for NH$_3$ much of the emission originates from manure management, with significant differences between winter and summer. In both Cumbria and Devon the total emissions are dominated by cattle, and consideration of this can be used to illustrate the expected time lags in emissions. Ammonia emissions from housing and grazing occur within a few days/weeks of excretion, and are expected to be reasonably closely coupled to animal numbers. By contrast, emissions from manure storage and land spreading of manures depend on the accumulation of manure over previous months. The main land spreading periods are spring and autumn, and a much smaller emission is expected if animals were not present in the previous six months winter housing period. This is the case with the 2001 outbreak of FMD. Restocking occurred throughout the spring of 2002, so methane emissions would be expected to increase directly. By contrast, a lag in reduced NH$_3$ emissions would be expected throughout the spring and early summer of 2002, due to a reduced store of animal manures from the 2001-02 winter housing period. In modelling the temporal course of NH$_3$ emissions following FMD, these lag effects were linked to the basic agricultural practice that is expected to cause seasonal variability in emissions. The consequence of these effects was that CH$_4$ emissions were estimated to have recovered more quickly than NH$_3$ emissions.

**Temporal emission profiles for areas not affected directly by FMD**

In order to model ammonia emissions on a monthly rather than annual basis, the agricultural management practices influencing emissions (e.g. livestock housing, manure application) need to be temporally disaggregated.

Seasonality needs to be considered for livestock housing/grazing periods, manure storage periods and manure and fertiliser application timings. A combination of survey data (ADAS Animal Manure Management Practice surveys, Manure Storage Area survey, British Survey of Fertiliser Practice) and expert opinion were used to generate a temporally disaggregated management activity profile for an average year.

**Spatial temporal distribution of emissions**

While IGER focused on estimating seasonal changes in total emissions, CEH applied a monthly version of the AENEID model to estimate the spatial distribution of emissions at a 5 km grid. This integrates the information on re-stocking with UK-wide statistics to give the spatially resolved national picture of emissions on a monthly level. Monthly spatially distributed estimates were derived for both ammonia and methane for January 2002 to January 2004.

In order to model ammonia emissions on a monthly rather than annual basis, the agricultural management practices influencing emissions (e.g. livestock housing, manure application) had to be temporally disaggregated. In addition, the effects of FMD in affected areas, such as reductions and/or delays in manure applications to land, on the temporal pattern of emissions had to be incorporated into the model.

June Agricultural Census data at the parish level were acquired for 2000–2003 from the devolved authorities for England, Wales and Scotland. These data are the main source of information for animal numbers in areas outside the two study areas (Cumbria, Devon and surrounding areas). For Cumbria and Devon and the surrounding counties, the parish level monthly cattle numbers from the BCMS (February 2002 – January 2004) were applied in the model. Monthly sheep and pig numbers for the affected areas were calculated using information about the timing of restocking (“freedom visits”) for estimating numbers between the June Census dates. Other livestock not affected by FMD (mainly poultry and horses) were assumed to be present in all areas of the UK without fluctuations in population on a monthly basis.
In order to model monthly emission spatially, the CEH/University of Edinburgh AENEID model (Dragosits et al. 1998, Dragosits 1999) had to be extended from an annual to a monthly basis. The new monthly version of AENEID was developed using monthly livestock numbers for the whole of Great Britain, calculated using a database containing June Census data for 2002-2003, total FMD cull data (autumn 2001), monthly cattle numbers from the BCMS, re-stocking algorithms for other affected livestock types affected by FMD, as well as monthly lamb numbers calculated using the algorithms described above. For 2002, the non-linearity effects in manure spreading emissions of NH$_3$ due to less manure accumulated during the winter housing period of 2001/2002 were also incorporated. This was achieved by calculating the landspreading emissions as a function of the number of livestock housed in each parish during the preceding winter housing period.

For the CH$_4$ estimates of AENEID, a new spatial and temporal distribution profile of source activities (e.g. livestock grazing, manure management) was derived for all livestock types. This was necessary to account for the different spatial distribution of the CH$_4$ emissions over the parish framework and the associated landcover data as compared with NH$_3$.

Spatially distributed fertiliser and crop emissions of NH$_3$, as well as all non-agricultural emissions for both NH$_3$ and CH$_4$ were added to the livestock emissions to ensure all sources were taken into account in the modelling approach, thereby allowing the comparison with measured concentrations. For fertiliser and crop emissions, a monthly profile of NH$_3$ volatilisation was derived from monthly estimates of IGER regarding use of different fertiliser types on arable crops and grassland. For the temporal distribution of non-agricultural sources, given the uncertainties and multiple contributing sources, it was assumed that there was no overall seasonal variation.

3.6. Work Package 6: Atmospheric transport modelling of ammonia and methane (CEH)

The monthly emission fields were input into the FRAME atmospheric dispersion model of CEH to calculate the spatial distribution of CH$_4$ and NH$_3$ concentrations on a 5 km grid resolution. For both NH$_3$ and CH$_4$, the standard version of FRAME (Version 5.1) was applied. This allows for chemistry, wet deposition and dry deposition for NH$_3$, in the case of CH$_4$, atmospheric chemical processes are extremely slow, and chemistry and wet deposition are excluded. The domain of FRAME includes the whole of the British Isles, therefore emissions from Northern Ireland and the Republic of Ireland are also included. For the purpose of this assessment, the Irish emissions, as well as the European import into FRAME, were assumed to be the same throughout the year. By contrast, in order to follow the time course of recovery, FRAME was applied on a monthly basis in relation to the emissions in Great Britain. It should be noted that the same statistical meteorology of FRAME was applied for all months, so that the modelled results represent only the effect of seasonally varying emissions. Other aspects of seasonality are currently being incorporated in FRAME (e.g. wind directions, wind speed, ammonia compensation points, wet and dry deposition), but these are beyond the scope of this study.

The results of the FRAME modelling were used to provide maps of modelled NH$_3$ and CH$_4$ concentrations through the monitoring period, as well as to provide estimates of concentrations for the 5 km grid squares containing the monitoring locations of this study.

3.7. Work Package 7: Interpretation and synthesis of results

Based on the above activities, the results were analysed to investigate the extent of consistency between modelled and measured changes in methane and ammonia concentrations. The results from FRAME were compared with the measurements on a monthly level for both NH$_3$ and CH$_4$. At the sampling sites, comparison between these two gases is particularly important, since CH$_4$ may be considered an inert tracer, while NH$_3$ has a
short atmospheric lifetime and is substantially affected by atmospheric chemical processes. Hence differences between the responses of the two gases may provide information that can be used to assess the importance of the atmospheric chemistry interactions for NH$_3$.

4. RESULTS

4.1. Estimated changes in animal numbers following FMD

Collation of data to estimate livestock numbers on a monthly basis was a substantial task. Three of the data sources were identified as providing useful information: the June agricultural census, BCMS and the State Veterinary Service. No further time was spent pursuing data from other sources. The most complete data set is that provided by the BCMS for cattle, which is important as cattle are the major source of ammonia emission from agriculture, particularly in Cumbria and Devon. Less robust data were available for other livestock types, but monthly estimates of animal numbers were feasibly based on the fixed points provided by the June census, the timeframe for restocking given by the State Veterinary Service and expert opinion on lambing times for the study areas.

Monthly total cattle numbers derived from BCMS data for Cumbria and Devon are summarized in Figure 5, showing the rate of re-stocking. Cattle numbers dropped sharply between March and May 2001, the drop in numbers being greater in Cumbria, where a much greater proportion of the county was affected by FMD. In Devon, numbers remained at the low point (94 – 95% of January 2001 numbers) for a prolonged period, May 2001 – April 2002 before recovering. In Cumbria, numbers continued to decline through 2001, reaching a low point (70% of January 2001 numbers) in November 2001, then beginning to recover. Recovery must be viewed against a trend of year on year declining cattle numbers. In Devon, recovery would appear to have been complete by June 2003, while in Cumbria numbers were still increasing slowly up to September 2003. In addition, there appears to be some within-year variation to beef cattle numbers, particularly seen as numbers dip in February/March 2003.

These patterns may be compared with the timing of the trace gas measurement period, which started at the beginning of February 2002. Hence, while a substantial period of low animal numbers was not included in the monitoring, restocking only began in December 2001, with the period of monitoring covering the main restocking changes. While it would have been desirable to include further monitoring during 2001, this would not have been possible due to site access restrictions.
Figure 5. Absolute and relative change in cattle numbers for the whole of Cumbria and Devon (derived from BCMS data). Note that detailed data have been collated for individual parishes to enable modelling within each county taking into account the smaller and larger relative changes observed at a finer resolution.

Monthly animal numbers by county, for the surrounding areas are shown in Figure 6. Cornwall and Somerset were largely unaffected by FMD, and the changes in cattle numbers for those two counties give an indication of the seasonal trends which might be expected in unaffected areas and years. Northumberland, Roxburgh (southern part of the Scottish Borders) and Dumfries were affected by FMD, to a similar extent as Devon. The cattle population of Roxburgh is relatively small in comparison to the other counties, so fluctuations appear larger on the percentage graph.
The State Veterinary Service (SVS) data proved valuable for checking the time course of restocking of animals and also covered other animal types apart from cattle (Figure 7 and 8). The first visit to a holding applying to restock has been labelled as the ‘restocking’ visit. At this time there would be a thorough site inspection to ensure that the disinfection protocols had been followed and on some occasions a few ‘sentinel’ animals would be left to see whether there was a reoccurrence of symptoms. These animals would be subject to a clinical inspection at the next visit to the holding. Several subsequent visits may have been made to the same holding as part of the procedure to obtain a restocking licence, but the important visit for restocking was the “freedom visit”, after which a farm was declared FMD free and allowed to resume normal practices (including restocking). Figure 8 shows that the timescale of the freedom visits was slower in Cumbria than in Devon (by 50-60 days). While the timescales for cattle and sheep were similar in Cumbria, in Devon the freedom visits occurred around a month later than for cattle.

Figure 6: Absolute and relative change in cattle numbers of cattle for areas surrounding Cumbria and Devon (derived from BCMS data).

FMD and trace gas changes
The SVS freedom visits provide the earliest dates that restocking could have occurred. However, for cattle the data support the BCMS data in terms of the timing of initiation of restocking. For Cumbria, 50% recovery in animal numbers had occurred by the start of March 2002, while 50% of the freedom visits were completed by start January 2002, indicating an approximate 2 month delay between recorded animal numbers and freedom visits. The BCMS data were considered more robust and were therefore used as the data source for cattle restocking.

For sheep, the June 2001 and 2002 census data provide fixed points for livestock numbers and monthly numbers between these 2 points were generated using the ‘freedom visit’ curves for Devon and Cumbria to provide the restocking start dates. Algorithms to fit these curves were derived (all with $R^2 > 99\%$), where $r\%$ is the percentage of the final restocking rate and $t$ is days after 1 June 2001.

![Graph showing the number of visits to livestock holdings in Devon according to the nature of the visit.](image)

**Figure 7:** State Veterinary Service visits to livestock holdings in Devon according to nature of the visit. The “freedom visit” refers to allowance for free animal movement and restocking.

![Graph showing the estimated time course for restocking in Cumbria and Devon.](image)

**Figure 8:** Estimated time course for restocking in Cumbria and Devon based on State Veterinary Service data of “freedom visits”.

_FMD and trace gas changes_
There are few pig farms in Devon and Cumbria, and therefore the number of pig farms visited by the SVS was too small in both counties for robust restocking dates for pigs to be derived. In this case the combined recovery profiles (Equations 1 and 4) were applied.

In relation to the timing of lambing, it was estimated for Devon that most lambing takes place in the period February to March, with a small percentage of sheep lambed in November and December and April (Kate Phillips, ADAS, pers. comm.). The profile for Cumbria is similar, but around 0.5 to 1 month later.

Sales of lambs for slaughter were generalised as follows: Early lambs (November – January) were estimated to be sold within 3 – 4 months, while February lambs would be sold by the end of June. Later lambs would be kept for between 6 – 8 months.

From this information, an estimate was made of the number of lambs alive in any given month (Figure 9). It is evident that the June census does not account for the maximum number of lambs alive during the year, as was expected. The June census can therefore be used as a fixed reference point and lamb numbers for other months calculated according to the distribution curves. Based on the distribution of Figure 9, it is estimated that the June census accounts for 78% and 93% of the total lambs born during the year for Devon and Cumbria, respectively.

4.2. Modelled temporal variation in methane and ammonia emissions

As noted above, the emissions of CH₄ derive mainly from eructation and are therefore expected to respond directly to animal numbers. By contrast, NH₃ emissions are connected with manure and fertilizer management and therefore a significant effort was placed to estimate temporal effects on NH₃ emissions.

\[
\% (\text{Devon, all livestock}) = 4E-12x^5 - 3E-09x^4 + 7E-07x^3 - 3E-05x^2 + 0.0002x + 0.0008 \quad (1)
\]

\[
\% (\text{Devon, cattle}) = 2E-13x^5 + 4E-10x^4 - 4E-07x^3 + 1E-04x^2 - 0.0021x + 0.004 \quad (2)
\]

\[
\% (\text{Devon, sheep}) = 6E-12x^5 - 5E-09x^4 + 1E-06x^3 - 8E-05x^2 + 0.0022x - 0.0007 \quad (3)
\]

\[
\% (\text{Cumbria, all livestock}) = 4E-14x^6 - 4E-11x^5 + 2E-08x^4 - 2E-06x^3 + 0.0001x^2 - 0.0031x + 0.0022 \quad (4)
\]
BASIC SEASONAL PATTERNS IN UNAFFECTED AND AFFECTED AREAS

The inventory of ammonia emissions for UK agriculture for the year 2001 was linked to a spreadsheet containing the monthly disaggregated activity data to generate a monthly emission profile for each source sector, taking account of typical average variation in management activities (Figure 10). A spring and autumn peak in emissions is obvious, separated by a summer trough. This profile is dominated by cattle, with lower emissions throughout the summer while cattle are grazing, and peaks in spring and autumn due to manure applications to land. Fertiliser applications enhance the spring peak, while poultry manure applications add to the autumn peak.

In practice, there are differences in the temporal pattern of management activities for different regions, due to climatic and soil differences, and for different years, due to specific weather conditions. However, robust data for these differences were not available and trying to incorporate them using expert opinion may increase errors introduced by assumptions already made. An additional source of error is in the emission factors used to generate monthly emission profiles. These are largely annual average emission factors for each source (some seasonality exists in the emission factor for slurry applied to land) but, in practice, are likely to be influenced by changes in temperature, rainfall, soil and crop conditions, etc. Ongoing research aims at linking emission factors more closely with climatic, soil and management factors but, as yet, such relationships have not been incorporated in the ammonia emission inventory structure.

TEMPORAL EFFECTS ON EMISSIONS IN FMD AFFECTED AREAS

FMD may have had some small knock-on effects on lambing dates for the following year (2002), although, anecdotally, this proved not to be the case. The major effect of FMD on the temporal emissions profile would be the extent to which cattle restocking had occurred before the winter housing period, thereby influencing the amount of manure generated over the winter for application over the following spring/summer/autumn. Manure applications during the following spring, summer and autumn (2002) would be related to the numbers of livestock housed during the winter of 2001/02, rather than the numbers of livestock present during the spring, summer and autumn months. Emissions from slurry stores might be assumed to have remained the same, as the surface area of slurry storage (which determines emission) is likely to have remained the same (but depths would be less). For solid manure, storage areas could
be assumed to have reduced in direct proportion to reductions in manure production over the
housing period.

Reductions in manure output over the 2001/2002 winter housing period are estimated at 17
and 3% for the whole of Cumbria and Devon, respectively. Therefore overall emissions from
land spreading and from storage of FYM should be reduced by this amount, although the
parish level reductions varied, with larger effects in affected areas. No changes in the
temporal pattern of manure spreading were thought to have occurred in 2002 as a knock-on
effect of FMD, so the temporal pattern in activities reflected the distribution above.

4.3. Modelled spatial temporal variation in ammonia and methane emissions

The resulting spatial-temporal distribution of NH₃ and CH₄ emissions is illustrated in Figures
11a and 11b, which show the total NH₃ and CH₄ emissions for Cumbria for the months of

Modelled emissions for June 2003 are lower than for February 2003, even though restocking
had occurred, due to the annual variation in emissions (with more manure spreading in
Spring). However, the increases between the months of February, June and October for 2002
and 2003, respectively, are clear.

The temporal pattern of modelled emissions varies according to location, depending on the
relative contribution of the different sources. This can be seen in Figure 12, which compares
the estimated ammonia emission for four example 5 km grid squares in Cumbria and the
Scottish Borders.

Figure 11a: Estimated ammonia emissions for selected months (February 2002, February 2003) following the
course of restocking after FMD in Cumbria.
Figure 11b: Estimated ammonia emissions for selected months (June 2002, June 2003, October 2002, October 2003) following the course of restocking after FMD in Cumbria.
Figure 12: Estimated time course of modelled ammonia emissions in four example grid squares around the Cumbria study area. Oakbank and Ayside are located in areas not directly affected by FMD, while Newton Reigny and Drumburgh Moss are located in areas affected by FMD (locations of sites shown in Figure 3)

The corresponding estimated emissions of methane for the months of February, June and October of 2003 and 2004 are illustrated in Figures 13a, 13b and 14. The increase in methane emissions with restocking occurs more quickly than for ammonia, which is due to emissions mainly being the result of eructation rather than manure management. The estimated seasonality in CH$_4$ emissions is much smaller than for ammonia. At Drumburgh Moss and Newton Reigny there was little seasonality in modelled emissions, as expected. By contrast higher emissions were modelled in the summer than the winter for Ayside and Oakbank East, and this may be attributed to the seasonality of cattle grazing on more extensive hill land in the summer, which changes the fine scale spatial pattern of emissions, and which is captured in the AENEID model.

Figure 13a: Estimated methane emissions for selected months (February 2002, February 2003) following the course of restocking after FMD in Cumbria.
Figure 13b: Estimated methane emissions for selected months (June 2002, June 2003, October 2002, October 2003) following the course of restocking after FMD in Cumbria.
4.4. Modelled ammonia and methane concentrations

The effect of the estimated CH₄ and NH₃ emission changes on modelled ground level (1-2 m) concentrations of these trace gases across the UK is summarized as maps in Figures 15-18. The high degree of spatial variability in modelled NH₃ concentrations and the small differences shown in many areas for the NH₃ concentrations and CH₄ concentrations above background (Figure 15, 17) is resolved in Figures 16 and 18 which show the differences between January 2002 (immediately after FMD, but prior to restocking) - January 2003 (0-1 year after end of FMD outbreak) and between January 2003 – January 2004 (1-2 year after end of FMD outbreak).

The blue areas of Figures 16 and 18 indicate areas where the modelled concentrations were larger in the later period (i.e. emissions and concentrations have increased, with recovery in animal numbers after FMD). The increase in modelled concentrations is apparent in Cumbria during both 2002 and 2003, but the increase in Devon was mostly limited to 2002. Other areas of the country with significant blue areas reflect other locations affected by FMD as well as other parallel changes in livestock numbers.

In addition, modelled NH₃ and CH₄ concentrations decreased at many locations in the UK over the same period (red areas in Figures 16 and 18). This is due to parallel reductions in animal numbers in other parts of the country not directly affected by FMD. For the modelled NH₃ concentrations, this includes reductions in cattle, pig, poultry and sheep numbers, while for methane, it reflects a reduction in cattle and sheep numbers across wide areas of the country. This effect is also seen in Figure 6 for Cornwall and Somerset. Due to limitations in data availability, the same livestock number estimates were used for Wales for January 2003 as January 2004, hence there is little difference in modelled concentrations across Wales for this comparison, showing how changes in local emissions dominate the changes in modelled concentrations, rather than non-local changes in emissions.

The more detailed temporal course in modelled NH₃ and CH₄ concentrations is shown in Figure 19 and 20 for two FMD-affected and two non-affected locations in Cumbria. The modelled ground level air concentrations change substantially from month to month.
(particularly for NH$_3$) and this is due to the combination of changing livestock numbers and monthly emission rates.

Figure 15: Modelled ammonia concentrations over Great Britain for three selected months following the recovery after FMD.

Figure 16: Modelled differences in ammonia concentrations between January 2002 to January 2003 and between January 2003 and January 2004.
Figure 17: Modelled enhancements in methane concentration above background for three selected months (January 2002, 2003 and 2004) following the recovery after FMD.

Figure 18: Modelled differences in ammonia concentrations between January 2002 to January 2003 and between January 2003 and January 2004.
Figure 19: Estimated time course of modelled ammonia air concentrations in four example grid squares in the “Cumbria” study area. The grid-squares at Oakbank and Ayside are located in areas not directly affected by FMD, while Newton Reigny and Drumburgh Moss are located in areas affected by FMD. The locations of these sites are shown in Figure 3.

Figure 20: Estimated time course of modelled methane concentrations above background in four example grid squares in the “Cumbria” study area. Oakbank and Ayside are located in areas not directly affected by FMD, while Newton Reigny and Drumburgh Moss are located in areas affected by FMD. The locations of these sites are shown in Figure 3.

In Figure 20 the modelled reduction in CH₄ concentrations due to FMD can be seen at the start of the measurement period for both Drumburgh Moss and Newton Reigny, with a large change in the first 3 months and a slower recovery to higher values in 2003 than in 2004. This pattern is also present for NH₃ in Figure 19, with larger values for matching seasons. However, it requires closer inspection to detect the trend for NH₃, as this is to a large extent masked by the substantial seasonal variations in emissions.

In order to demonstrate the recovery more clearly for NH₃, a comparison is made in Figure 21 between selected FMD-affected and FMD-unaffected sites in Cumbria where the model predicted the largest and least change respectively. To construct Figure 21, the monthly ammonia concentration for each monitoring site was normalized to the site mean, and then plotted as a percentage of the mean normalized monthly concentration for all the unaffected sites. This provides a convenient method for distinguishing the FMD-affected and FMD-unaffected sites, which factors-out the basic seasonal variation in unaffected sites. The
variation in the structure between sites is due to both the extent of FMD in the localities and the different mix of contributing agricultural source sectors.

Figure 21: Estimated changes in FRAME modelled NH₃ concentrations at selected monitoring sites in Cumbria. The modelled monthly NH₃ concentration normalized for each site is shown as a percentage of the mean normalized concentration for all the unaffected sites. The modelled reduction in normalized NH₃ concentration is clearly shown for the sites in FMD-affected areas (see Figure 3).

4.5. Measured ammonia and methane concentrations

The time-course of measured NH₃ and CH₄ concentrations may be illustrated by results from example sites. Figures 22 and 23 compare example sites in Cumbria and Devon, respectively, which show substantial temporal variability.

The variability is most clear for NH₃, which showed occasional peak concentrations at certain sites. For example, at Raughton Head, Calbeck School and Newton Reigny peak concentrations of ammonia were recorded in December. As the ALPHA sampling for NH₃ was based on triplicate sampling and coefficients of variation were uniformly low, it is clear that these peaks represent real increases in NH₃ concentrations. The explanation appears to be that when the ground is frozen, farmers are able to access fields and apply liquid and solid animal manures to fields. Although this is not consistent with crop needs and Codes of Good Agricultural Practice, this allows the disposal of the manures, which may be necessary where storage capacity is limited. Such wintertime peak NH₃ concentrations have also been recorded widely over recent years in the NAMN measurements. Other smaller peaks in NH₃ concentration are seen at these sites in spring (May-April) and autumn (August, September), which are consistent with the established and recommended practices for manure spreading.

The temporal variability in CH₄ concentrations at sites in Cumbria shows a combination of regional and local effects. Peak concentrations were seen in certain months (e.g. April 2002, December 2003), and this may be due to a combination of meteorological stability and emissions of CH₄ following manure spreading, a source which may have been underestimated in the inventories. In addition, certain sites show significant fluctuation in concentrations, such as Bucknill’s Field, with a peak concentration in August 2002. The most likely
Believe in the presence of local intermittent sources (e.g. vehicle or local gas sources) or uncertainty in the measurements.

Figure 22: Time course of measured NH₃ and CH₄ concentrations at example monitoring sites in Cumbria, selected to illustrate differences in seasonal patterns.

The NH₃ concentrations in Devon showed broadly similar patterns to those in Cumbria, although only a few sites showed winter peak concentrations. In Figure 23, these peak concentrations were seen at Holsworthy Beacon (December 2002) and Shebbear (January 2004). The lower occurrence of winter peak NH₃ concentrations in Devon, compared with Cumbria may be attributed to the lower occurrence of frosts, limiting winter access to fields for manure spreading. At the sites in Devon, the peak concentrations in March-April and August-September are much more marked (Shebbear, Highampton, Upcott). The site at Upcott provided unusually large NH₃ concentrations in summer 2003, and correspondingly small concentrations in winter. This may be explained by fields immediately adjacent to this measurement station being intensively grazed during summer 2003.

Figure 23 shows little relationship between the measured CH₄ and NH₃ concentrations at sites in Devon, making it difficult to explain the observed CH₄ concentrations patterns. The NH₃ peaks associated with periods of manure spreading do not in this case coincide with peaks in CH₄ concentrations. In addition, there were substantial gaps in the CH₄ dataset for Devon, which was due to more frequent failure of the bag sampling system at these sites.

The data capture of the different measurements and study areas may be expressed as the percentage of data available following loss of samples or removal of data failing quality standards, or other outliers. For NH₃ the data capture for the FMD sites was 97% in Cumbria and 97% in Devon. For CH₄ the data capture for the FMD sites was 95% in Cumbria and 75% in Devon.
Maps for the measured CH\textsubscript{4} and N\textsubscript{2}O were provided and discussed in the first interim report to Defra (Sutton \textit{et al.} 2002) and are not repeated here. In the following, we focus on a) the comparison of measurements in affected and unaffected areas and b) the comparison of the measured values with the model estimates.

4.6. Comparison of measured concentrations in areas affected and not-affected by FMD

In order to highlight the effect of restocking following FMD, the analysis of the initial data has compared sites in areas with a large reduction in emissions expected due to FMD with areas that were little affected. Of the 20 sites funded under this project in each of Cumbria and Devon, most were selected in areas of large effects of FMD. Hence in Cumbria 16 sites were in FMD affected areas and 4 in surrounding (little affected/control) areas. In Devon 15 sites were in FMD affected areas and 5 were in surrounding non-affected areas. Additional sites with little effect of FMD may be found from the NAMN and MANE monitoring networks, and these were also used to contribute to the analysis.

However, particularly in the Cumbria-centred study area, several of the NAMN sites are in areas with an intermediate effect of FMD, and with different background emissions. Therefore they are not fully relevant for comparison to highlight the effects. Similarly, some of the NAMN sites had seasonal patterns in NH\textsubscript{3} exchange which were very different to the FMD affected areas. As these seasonal differences would mask any effect of FMD, these sites were also not used. This in particular concerned background sites, where emissions were dominated by sheep at Sourhope, Cardoun Burn, Coalburn and Moorhouse. These
"intermediate" sites also had very different NH₃ concentrations from the other sites (Figure 24) justifying their exclusion from further analysis.

![NH₃ concentrations diagram](image)

**Figure 24**: Comparison of NH₃ concentrations (µg NH₃ m⁻³) at sites affected or not affected by FMD for the Cumbria centred study area. The figure includes data from all available nearby NAMN sites shown in Figure 3.

### 4.6.1. TEMPORAL TRENDS IN AMMONIA CONCENTRATIONS

The results for NH₃ from the 20 FMD monitoring sites in Cumbria and the 20 sites in Devon are shown in Figures 25 and 26. In the first part of each graph (A) the mean of the actual NH₃ concentration is shown for the affected vs. unaffected sites. Although there are differences in the detail, the overall pattern is similar, i.e., relative to the unaffected sites the concentration at the FMD affected sites increases with time. This feature occurs in both Cumbria and Devon, and is seen more clearly by normalizing the concentrations to highlight the trends. In this normalization, the concentration for each month at each site is divided by the mean biennial concentration at the site. The mean of these site-normalized concentrations is then shown in Figures 25 and 26 (B) for FMD-affected and -unaffected sites. The normalization ensures that all sites give equal weight to the trend for the group averages of affected vs. unaffected sites.

The direct plots of NH₃ concentration (Figures 25 and 26 A) show how the concentrations at FMD-affected sites appear to increase with time, but this is difficult to detect, given the different mean concentrations at FMD-affected and unaffected sites and the seasonal variation. The plots of mean site normalized concentrations (Figures 25 and 26 B) make the comparison more clear: For both Cumbria and Devon, the normalized concentrations are smallest at FMD-affected sites at the start of the period, and largest at FMD-affected sites at the end. This supports the interpretation that NH₃ concentrations are detected as recovering in parallel with restocking after FMD.

While this may be considered a rather important and exciting finding (in that it lends support to the current modelling and assessment approaches), there are several caveats that need to be addressed. For the changes seen in 2002, a key limitation is that NH₃ concentrations at the affected and unaffected sites have the same seasonal cycle. If there is a significant difference in the normal seasonal cycle between these groups of sites, then the attribution to recovery after FMD could have been an artefact. However, the continuation of the measurements in 2003 shows that although there is some seasonal cycle, this cannot explain the overall trend in the data. As a result, the measurements support the interpretation of recovery in NH₃ concentrations following restocking after FMD.

The fact that the NH₃ concentrations remained low until late summer 2002 at the affected sites may be explained by the lag-effect noted above (Section 3.5, Work Package 5), whereby...
emissions from land-spreading of manures are reduced due to lower availability of manure in
FMD affected areas.

![Graph showing temporal trend of NH₃ concentrations around Cumbria comparing FMD-affected and unaffected areas. A. Mean NH₃ concentrations; B. Mean NH₃ concentrations based on data normalized for each site to highlight temporal trends and minimize the effect of inter-site differences in average concentration.]

**Figure 25:** Temporal trend of NH₃ concentrations around Cumbria comparing FMD-affected and unaffected areas. A. Mean NH₃ concentrations; B. Mean NH₃ concentrations based on data normalized for each site to highlight temporal trends and minimize the effect of inter-site differences in average concentration.

![Graph showing temporal trend of NH₃ concentrations around Devon comparing FMD-affected and unaffected areas. A. Mean NH₃ concentrations; B. Mean NH₃ concentrations based on data normalized for each site to highlight temporal trends and minimize the effect of inter-site differences in average concentration.]

**Figure 26:** Temporal trend of NH₃ concentrations around Devon comparing FMD-affected and unaffected areas. A. Mean NH₃ concentrations; B. Mean NH₃ concentrations based on data normalized for each site to highlight temporal trends and minimize the effect of inter-site differences in average concentration.

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4.6.2. TEMPORAL TRENDS IN METHANE CONCENTRATIONS

The temporal trends for CH₄ are expected to differ substantially from those for NH₃, since most CH₄ emissions occur directly from animals with only a small annual variation. Figure 27 shows however, that there are some unexpected similarities in the trends for CH₄ with those for NH₃. The highest concentrations of CH₄ (for both affected and non-affected sites in Cumbria and Devon) occur in spring and autumn, with an additional peak in Cumbria occurring in December 2003. Although there is substantial scatter in the data, this timing suggests that manure management may have a larger influence on atmospheric CH₄ concentrations relative to eructation than previously estimated, e.g. in the National Atmospheric Emissions Inventory.

The comparison of CH₄ concentrations in FMD-affected and non-affected areas shows a much less clear difference than that seen for NH₃ (Figures 27 and 28).

![Figure 27](image-url)

**Figure 27:** Temporal trend of CH₄ concentrations around Cumbria comparing FMD-affected and unaffected areas. A. Mean CH₄ concentrations; B. Mean CH₄ concentrations based on data normalized for each site to highlight temporal trends and minimize the effect of inter-site differences in average concentration.
4.6.2. TEMPORAL TRENDS IN NITROUS OXIDE CONCENTRATIONS

Although CH₄ was used as the main tracer gas for comparison with NH₃ concentrations, the N₂O data permit further comparison. The time course of N₂O concentrations is highly variable in source areas, reflecting the combination of different sources contribution to emissions. Figures 29 and 30 compare the measured N₂O concentrations in FMD-affected and unaffected areas. These figures show a close similarity between N₂O concentrations between the site groups of affected vs. unaffected areas. In addition, there is also substantial similarity between the concentrations measured in the Cumbria and Devon study areas between months. For example, for both areas concentrations of N₂O were low in June 2002 and June 2003, but high in May and July for both years. This suggests that region-wide seasonal factors are responsible for fluctuations in N₂O concentrations. Analysis under the MANE project indicates links to synoptic scale meteorological variability affecting soil temperature and wetness, as well as to the timing of nitrogen fertilizer application.

Unexpectedly, both the Cumbria and Devon study areas show slightly larger N₂O concentration during the initial phases of restocking after FMD in FMD-affected areas than unaffected areas. Nitrous oxide emissions are characterised by very large spatial and temporal variability, however one may speculate that the difference could have been induced by soil compaction, grazing and fertilization on fields that have not had this impact during the FMD period.

Figure 28: Temporal trend of CH₄ concentrations around Devon comparing FMD-affected and unaffected areas. A. Mean CH₄ concentrations; B. Mean CH₄ concentrations based on data normalized for each site to highlight temporal trends and minimize the effect of inter-site differences in average concentration.
Figure 29: Temporal trend of N\textsubscript{2}O concentrations around Cumbria comparing FMD-affected and unaffected areas. A. Mean N\textsubscript{2}O concentrations; B. Mean N\textsubscript{2}O concentrations based on data normalized for each site to highlight temporal trends and minimize the effect of inter-site differences in average concentration.

Figure 30: Temporal trend of N\textsubscript{2}O concentrations around Devon comparing FMD-affected and unaffected areas. A. Mean N\textsubscript{2}O concentrations; B. Mean N\textsubscript{2}O concentrations based on data normalized for each site to highlight temporal trends and minimize the effect of inter-site differences in average concentration.
4.7. Comparison of measured and modelled concentrations of NH₃ and CH₄

Figures 25 to 30 record the overall change in the measurements following FMD. However, it remains difficult to distinguish the signal of FMD in these graphs. In addition, it is of particular interest to relate the observed changes to those expected, based on the modelling.

The results of the measurements and modelling for NH₃ and CH₄ are combined in Figures 31 to 34, for both gases and study areas. In the figures, the measured and modelled concentrations are first compared directly (a). Secondly, the measurements and modelling are compared for the site-normalized concentrations (b). In this approach, the monthly concentration at each site is divided by the mean concentration at the site for all months, to normalize the concentration to all sites to a value of 1. This has the advantage to give equal weighting to all sites in the calculation of the means, and has the result that the monthly normalized concentrations vary around 1. Thirdly, for each of the measured and modelled series, the value of the FMD-affected mean of the normalized values is plotted as a percentage of the FMD-affected mean (c). These values are corrected so that the period October 2002 to January 2004 has an average of 100%, based on the observation that restocking following FMD was complete by October 2002.

4.7.1. AMMONIA

Figures 31 and 32 show an encouraging comparison for the time course of seasonal NH₃ concentrations for the model versus measurements. The spring and autumn peaks in measured NH₃ emissions are reproduced by the model, but not the winter peaks in NH₃ concentration observed mostly in Cumbria. This implies that the national NH₃ inventory needs to be corrected to include the actuality of manure spreading to frozen soils.

On average, the NH₃ concentration estimate of the model is larger than the measurements. This may have a number of causes, including average location of sampling points in model grid squares and uncertainty in parameterisation of dispersion in the model, and does not necessarily imply an overestimation of NH₃ emissions. This feature is not critical for the present purpose, since it is seen to occur in both the FMD-affected and unaffected areas.

The third part of Figures 31 and 32 (c) provide the key results of this study. For both the Cumbria and Devon study areas, the NH₃ concentration is found to have been depleted in FMD-affected areas (start 2002) and then to have recovered following the course of animal restocking. The comparison with the measurements is extremely encouraging, and, if anything, the measured NH₃ concentrations were found to have been more depleted in FMD affected areas than suggested by the modelling. In addition, both the measurement and model time courses show how NH₃ concentrations continued to increase through 2003, as a result of ongoing restocking.

The trends with time of the model and measurements are rather scattered. For Cumbria, both the model and measurements showed a statistically significant upward trend with time (P<0.001), but the two trends were not significantly different from each other (P=0.08). For Devon, the model trend was not significant (P=0.07), while the measured trend was significant (P=0.01), with the lower correlations with time for Devon being due to the underlying seasonal variability.

4.7.2. METHANE

Figures 33 and 34 show the time course of the comparison between measurements and model for CH₄. The series of graphs is the same as for NH₃, except that the two normalized graphs are based on modelled and measured concentration enhancements above background, while the non-normalized graph includes the background. Background concentrations for the same...
period were taken from measurements at the Shetland observatory (CSIRO Atmospheric Research GASLAB, see Francey et al. (1998) for methodology).

Figure 31: Comparison of measured and modelled NH$_3$ concentrations in FMD-affected and unaffected areas of Cumbria: a) mean concentrations at sites, b) mean of normalized monthly concentrations (monthly concentrations of each site normalized to overall site mean), c) mean of FMD-affected sites as a percentage of unaffected sites, from normalized data based on full recovery by October 2002.

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Figure 32: Comparison of measured and modelled NH$_3$ concentrations in FMD-affected and unaffected areas of Devon: a) mean concentrations at sites, b) mean of normalized monthly concentrations (monthly concentrations of each site normalized to overall site mean), c) mean of FMD-affected sites as a percentage of unaffected sites, from normalized data based on full recovery by October 2002.
Figure 33: Comparison of measured and modelled CH₄ concentrations in FMD-affected and unaffected areas of Cumbria: a) mean concentrations at sites, b) mean of normalized monthly concentrations above background (monthly concentrations of each site normalized to overall site mean), c) mean of FMD-affected sites as a percentage of unaffected sites, from normalized data based on full recovery by October 2002.
Figure 34: Comparison of measured and modelled CH₄ concentrations in FMD-affected and unaffected areas of Devon: a) mean concentrations at sites, b) mean of normalized monthly concentrations above background (monthly concentrations of each site normalized to overall site mean), c) mean of FMD-affected sites as a percentage of unaffected sites, from normalized data based on full recovery by October 2002.
By contrast to the comparison for NH$_3$, the temporal agreement between the model and measurements of CH$_4$ is not very close. This is mainly attributable to the value of the remote background used (from Shetland), which was added to the modelled values. The uncertainty introduced by the background value used is largely avoided in the normalized plots. The percentage graph of FMD-affected sites versus unaffected sites shows depletions in modelled concentrations above background down to 83% for Cumbria and 94% for Devon, respectively, with these values quickly recovering over the following months. However, it is not possible to detect these trends in the measurements. Although the percentage reduction in affected areas compared with unaffected areas roughly tracks the modelled value, the scatter in the normalized measured line is too large to detect significant relationships. The scatter in the measured methane concentrations is larger in Devon than in Cumbria, due to a lower data capture in Devon (more system failures and more outliers). For Cumbria, where the data capture was very high (95%), the scatter in the measurement must be attributed to other sources (e.g. local variability in CH$_4$ sources at the landscape level, measurement precision).

5. DISCUSSION AND CONCLUSIONS

5.1. Detection of the “FMD ammonia signal” and policy implications

This study was motivated by the uncertainty in ammonia emissions abatement implied in different European assessments, which were unable to link a decrease in estimated ammonia emissions with an expected decrease in atmospheric concentrations (Erisman et al. 1998; van Jaarsveld et al. 2001, Sutton et al. 2003). In the Netherlands, this discrepancy has become known as the “Ammonia Gap”, and several reasons have been suggested as explanation. These include the suggestion that the abatement measures were not as effective as had been hoped, non-linear interactions in the context of changing pollution climate, interactions with the ammonia compensation point and spatial/temporal variability. In Eastern Europe, it was found to be difficult to observe expected reductions in ammonia, even though this was purely related to changes in animal numbers and fertilizer use, and therefore not related to the efficacy of emission abatement techniques.

The present study has provided the opportunity to test the link between ammonia emissions and monitored air concentrations after the dramatic reductions in animal numbers associated with Foot and Mouth Disease. As such, it tests whether there are in principle limitations that mean that ammonia concentrations are not directly related to emissions. The parallel measurement of methane concentrations was aimed to provide assessment of an inert tracer. Concentrations of this tracer ought to be directly related to emissions, since in rural areas with intensive livestock, CH$_4$ enhancements above background concentration are a direct function of emission and the same dispersion mechanisms that govern ammonia concentrations, but this does not involve rapid atmospheric reactions or compensation points.

The results of the study are therefore both encouraging as regards the ammonia and surprising as regards the methane. Through a programme of monthly measurements over just two years, it has been possible to demonstrate recovery in ammonia concentrations following restocking after FMD. Coupled modelling of monthly ammonia emissions and atmospheric concentrations at 5 km resolution has shown that the measurements and model are broadly consistent. In the present project, the measurements demonstrated the expected increase in ammonia concentrations. However, this detection of the FMD signal is of equal relevance for situations where ammonia emissions are reduced. The results of this study show that, where ammonia emissions are reduced on a regional scale in source areas, it is possible to demonstrate the anticipated outcome in terms of reduced ammonia concentrations. This information is vital as a basis for future ammonia abatement policies.

The comparison of two contrasting areas, centred on Cumbria and Devon, proved instructive as regards the detection limits of change. Based on an initial modelling assessment (Sutton et
it was expected that in the worst affected areas of Cumbria ammonia concentrations would reduce by 40-50%, while in the worst affected areas of Devon they would reduce by 20-30%. These values and the difference between the two study areas are broadly consistent with the more detailed assessment here. In this case, however, the analysis has focused on the grid locations of the selected monitoring locations, comparing the mean of a set of FMD-affected sites and surrounding sites, which were not directly affected by FMD. In this case the modelled reductions of the affected sites are around 20-30% and 5-10%, for Cumbria and Devon, respectively. It should also be noted that the numbers are not precisely comparable. The initial assessment (Sutton et al. 2004b) compared the situation immediately before and after FMD, while this study assesses the extent of change from immediately after FMD to the year after, when full recovery is assumed. Based on the approach used here of a parallel measurement of two groups of sites (affected, unaffected), the results shown in Figures 31 and 32(c) indicate that the minimum detectable change in two years sampling is of the order of 10-20%.

It should be obvious that with the inclusion of more monitoring sites, or changes occurring over a longer period, it should be possible to detect smaller differences. By contrast, in the absence of a parallel reference (the unaffected sites), only larger differences would be detectable. Hence in Figure 29 (a) the increase over time in measured NH$_3$ at the FMD-affected sites would not be significant. The matching reference sites are thus essential in order to factor out normal seasonal changes resulting from agricultural management cycles and changes in environmental conditions. A key caveat is that the reference sites should otherwise be as similar as possible, i.e. similar mean concentrations, main source sector types, land types and normal seasonal profile. Thus in this study, it was necessary to exclude some monitoring sites (e.g. Sourhope, Cardoun Burn, Moorhouse), where the seasonal concentration profiles were very different (summer maxima) and typical of upland rather than lowland areas.

5.2. Uncertainties in detection of the CH$_4$ signal

Despite the expectation that CH$_4$ would provide a clear signal, unperturbed by chemical or other interactions, this turned out not to be the case. The uncertainties in the measured CH$_4$ concentrations were larger than the modelled signal of change. Firstly, it should be noted that the modelled changes are smaller than those estimated in the prior assessment (Sutton et al. 2004b). It appears that this is a result of smaller changes in recovery after FMD than were estimated to have occurred at the start of FMD, and due to not all the sites being in the worst affected areas. It may also result from uncertainty in the real background CH$_4$ in these areas, as the estimated background CH$_4$ concentration (from Shetland) was necessary to be added to the modelled enhancement above background due to local agricultural sources, to compare the model with the measurements.

Two other reasons may help explain why the measurements have not succeeded in detecting the expected changes in CH$_4$ concentrations: local level variability in CH$_4$ emissions and sampling precision.

Although the AENEID model indicates that livestock is the major CH$_4$ source in the regions studied, there may be substantial local variability in CH$_4$ emissions and concentration enhancements. As a result, sites near villages or roads may be affected by combustion sources or natural gas leaks and landfill emissions, while there will also be patchiness in the biogenic emissions. To assess this effect in more detail requires denser sampling of CH$_4$ concentrations, such as at the landscape scale, as has previously been done for ammonia (Duyzer et al. 2001, Tang et al. 2000, Theobald et al. 2004).

Although laboratory tests indicated good reproducibility of the foil bag approach, it is possible that reproducibility is not as good in the field, and there is a hint of this in the lower quality (less precise, lower data capture) dataset obtained from Devon than from Cumbria. It is not clear what caused the difference in data quality between the two study areas, but it
points to the need for field replication of the CH₄ sampling systems, in the same way as was made for NH₃ (e.g. triplicate samplers).

5.3. Modelling spatio-temporal patterns in NH₃ and CH₄ emissions and concentrations

A major part of this study was the acquisition and processing of large livestock datasets to estimate the spatio-temporal patterns in ammonia emissions. The major data sources were acquired from the British Cattle Movement Society, State Veterinary Service and the annual parish census data conducted for Defra and the Devolved Administrations.

By combining these data, it was possible to model ammonia emissions spatially for the UK and specific regions at a monthly level for the first time. The major uncertainty in calculation of the seasonal distribution of emissions is the basic profile of agricultural activities and ammonia emissions under “normal practice”. This is based largely on expert information, which may be incomplete, and does not take account of interactions with environmental conditions. Thus the measurement showed that winter-time spreading of manures onto frozen fields was more important than supposed in the inventory. In addition, the fact that the winter peaks in NH₃ concentration were more frequent in Cumbria than Devon, is consistent with the warmer winters that occur in Devon than in Cumbria.

5.4. Implications for air monitoring strategies

This study has significant implications for rural air monitoring strategies. There has recently been significant debate in Europe over the relative merits of implementing a) low frequency monthly measurements at very many sites, b) manual daily monitoring at key regional sites and c) advanced continuous multi-species monitoring at a few European “super sites” (e.g. UNECE 2004; Sutton et al. 2004a). It was agreed that these different sampling levels serve the different complementary objectives in such monitoring and that more than one approach is needed. However, the emphasis differs. In a review of European monitoring of reduced nitrogen Sutton et al. (2004ab) identified the example of reduced ammonia emissions in East Germany compared with West Germany during the 1990s. A detailed wind sector analysis of one site on the border of East and West Germany was not able to detect the signal of reduced emissions in East Germany (Acker et al. 1998). By contrast, a simple analysis of rain chemistry records by averaging multiple monitoring sites in all eastern and western Federal States of Germany was able to demonstrate the expected trend. For the objective of trend evaluation, this points out the dangers of detailed interpretation of single sites, which due to local conditions (microclimate, nearby sources, nearby sinks etc) may not be completely representative.

The trends observed in this study were determined using two networks of 20 sites, supplemented by suitable nearby sites. For the Cumbria study area, 17 sites were in affected areas and 5 sites in unaffected areas. For the Devon study area, 16 sites were in affected areas and 5 sites in unaffected areas. It was expected to have more sites in unaffected areas from the national networks. However, many of these turned out to be unsuited due to different source types and seasonal profiles, with strong summer maxima. The importance of using these multiple sites may be demonstrated by restricting the analysis to fewer sites. For example, it might be supposed that a clearer result would be obtained by restricting the comparison to the most affected sites and the least affected sites. The results of the FRAME modelling were used to filter the sites in the Cumbria study area for those sites where modelled reductions were more than 30% (most affected) and those where reductions were less than 10% (least affected). This reduced the dataset to 8 affected sites and 5 unaffected sites (as shown in Figure 21, excluding Oakbank East). The results of this assessment are shown in Figure 35. The selection of more extreme sites resulted in a larger modelled mean reduction (affected as a % of unaffected down to 65%), and the measured reduction is also more (affected as a % of unaffected down to 53%). However, the scatter in the measured trend is substantially larger than when using the full dataset available, making this comparison
much less convincing than that shown in Figure 31. This demonstrates the importance of networks with many sites and combined analysis as an essential basis for trend assessment.

![Figure 35: Comparison of measured and modelled NH₃ concentrations in FMD-affected and unaffected areas of Cumbria, using a restricted dataset of sites most-affected and least affected by FMD. The graph shows mean of FMD-affected sites as a percentage of unaffected sites, from normalized data based on full recovery by October 2002 and should be compared with Figure 31c. Although the signal is larger when using the reduced number of monitoring sites, the measured trend is substantially less certain, demonstrating the need for assessments based on multiple monitoring sites.](image)

**Acknowledgements**

The authors are grateful to Defra for funding this project (AM0118) and the preceding pilot project (AM0116), as well as the CSIRO Atmospheric Research GASLAB remote monitoring station in Shetland, Scotland, for background CH₄ concentration data for the study. The British Cattle Movement Society are thanked for providing details of cattle on agricultural holdings on a monthly basis and the State Veterinary Service for providing details of the timing of restocking visits to affected areas.

6. REFERENCES


