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Ammonia Emissions from Broiler Litter and Laying Hen Manure Management Systems

F.A. Nicholson; B.J. Chambers; A.W. Walker

ADAS Gleadthorpe Research Centre, Meden Vale, Mansfield, Nottinghamshire, NG20 9PF, UK; e-mail of corresponding author: fiona.nicholson@adas.co.uk

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Poultry farming accounted for an estimated 16% of ammonia emissions from UK agriculture in 1999. This study investigated the potential to reduce ammonia emissions by altering the ways in which poultry manures are managed. Ammonia loss measurements were made from complete broiler litter and laying hen manure management cycles (housing → manure handling → storage → land spreading). Ammonia losses were higher (probability $P<0{\cdot}05$) from winter-housed broilers on straw (mean 2·0 g $[NH_3\text{-}N]\,h^{-1}$ 500 kg^{-1}[liveweight — lw]) than from those on woodshavings (mean 1·0 g $[NH_3\text{-}N]\,h^{-1}$ 500 kg^{-1}[lw]), but there were no differences in emissions ($P>0{\cdot}05$) between different litter types/rates during storage and following land spreading. The overall balances of ammonia emissions from broiler litter during housing, storage and following landspreading were 28, 15 and 57%, respectively. In the laying hen housing studies, ammonia losses from weekly belt-scraping (mean 3·3 g $[NH_3\text{-}N]\,h^{-1}$ 500 kg^{-1}[lw]) were more than double ($P<0{\cdot}05$) those from daily belt-scraping (mean 1·3 g $[NH_3\text{-}N]\,h^{-1}$ 500 kg^{-1}[lw]), with twice weekly belt-scraping estimated to reduce ammonia losses by *ca*. 50% compared with weekly cleaning. Ammonia losses from a commercial deep pit house (8·2 g $[NH_3\text{-}N]\,h^{-1}$ 500 kg^{-1}[lw]) were higher ($P<0{\cdot}05$) than from belt-scraped (2·7 g $[NH_3\text{-}N]\,h^{-1}$ 500 kg^{-1}[lw]) or stilt (1·4 g $[NH_3\text{-}N]\,h^{-1}$ 500 kg^{-1}[lw]) houses, but there were no differences between manures from the three housing types (deep-pit, belt-scraped or stilt houses) during storage or following land spreading. The overall balance of ammonia emissions from laying hen manures during housing, storage and land spreading was 51, <1 and 48%, respectively. These findings indicate that strategies to reduce ammonia emissions from poultry farming would be most effective if focused on housing and land spreading practices where the greatest loss of ammonia occurs.

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1. Introduction

Ammonia volatilisation represents a substantial loss of fertiliser nitrogen (N) value when manures are applied to agricultural land (Anon, 2000). Moreover, environmental damage may be caused following ammonia deposition through direct toxicity to plants (van der Eerden, 1982), changes in plant species composition of natural ecosystems (Heil & Diemont, 1983), eutrophication and soil acidification (van Breemen & van Dijk, 1988). Following implementation of the European Council Directive on Integrated Pollution Prevention and Control (IPPC; EA, 2000), member states are required to prevent or reduce pollution in order to achieve a high level of protection for the environment. As part of this overall objective, the UK government is required to take action to reduce ammonia emissions from large pig and poultry units (MAFF, 1997). In addition, further information is required on practical and cost effective ways of reducing ammonia losses from livestock systems to enable the UK to comply with the National Emissions Ceiling Directive target of reducing ammonia losses to less than 297 kt ammonia (NH_3) by 2010 (EC, 2001).

Around 4 million tonnes of poultry manure are produced annually in the UK, with ammonia-N losses

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estimated at 39 kt in 1999, equivalent to *ca.* 16% of estimated ammonia emissions from UK agriculture (Misselbrook, 2000). Housing losses from laying hens were estimated at *ca.* 4 g [NH_3-N] h^{-1} 500 kg^{-1}[liveweight — lw], and from broilers at 4·5 g [NH_3-N] h^{-1} 500 kg^{-1} [lw]. However, the Inventory of Ammonia Emissions from UK Agriculture (Misselbrook, 2000) did not take into account the influences of different laying hen manure management systems on ammonia emissions or the subsequent effect of housing emissions on ammonia losses during storage and following land spreading. Similarly, the influence on ammonia emissions of broiler litter management (e.g. type and quantity of bedding material; drinker systems), which is likely to affect litter moisture content and hence the rate of conversion of uric acid to ammonium-N (Sims & Wolf, 1994), was not taken into account in the Inventory (Misselbrook, 2000).

Previous UK studies (*e.g.* Chambers & Smith, 1998; Pain *et al.*, 1998; Chambers *et al.*, 1997) have largely focused on measuring ammonia losses from individual components of poultry manure management systems (*i.e.* buildings, stores, land spreading), which has limited the ability of desk study exercises to make balanced system comparisons. Clearly ‘upstream’ losses (*e.g.* from housing) have a profound effect on those occurring ‘downstream’ (*e.g.* from land spreading). It is therefore important, if valid conclusions are to be drawn on ammonia emissions from each system or on the effectiveness of abatement techniques, that measurements follow through the whole manure management continuum (buildings → manure handling → storage → land application).

The objective of this study was to quantify and compare ammonia losses from different broiler litter and laying hen manure management systems, and the individual components of each manure management system. Ammonia is a highly reactive gas that is normally only present in air at trace concentrations and is therefore difficult to measure. A number of different methods of measuring ammonia emissions have been developed, the suitability of which depends largely on the system under study. Both acid traps (Lockyer, 1983) and diffusion tubes (Hargreaves & Atkins, 1987) could potentially be used for measuring emissions from poultry housing. A further objective of this study was therefore to establish the most suitable method for measuring ammonia losses from broiler and laying hen housing.

2. Materials and methods

2.1. *Poultry housing systems*

Studies were undertaken at a poultry research facility at ADAS Gleadthorpe, Nottinghamshire, UK (broiler chickens and laying hens) and a commercial poultry unit in Leicestershire, UK (laying hens).

2.1.1. *Broiler chickens—ADAS Gleadthorpe Research Centre*

Broiler chickens were housed at ADAS Gleadthorpe in a climate facility with eight independently controlled rooms. Lighting was provided by tungsten bulbs and heating was provided by radiant gas brooders. The house was equipped with a pressurised ventilation system operating through a thermostatic control panel. The initial ambient temperature at day old was 31 °C and was decreased by 1 °C per alternate day until the temperature reached 21 °C by day 21. The post-brooding target temperature was 21 °C. The minimum ventilation rate was calculated to supply $1{\cdot}9 \times 10^{-4}$ m^3 [air] s^{-1} $kg^{-0{\cdot}75}$ [lw] and this rate was supplied by one 480 mm fan. Feed was available ad libitum through a pan feeder system and water was provided via bell or nipple drinkers (depending on the experiment). Litter was provided in the form of clean woodshavings or straw.

2.1.2. *Laying hens—ADAS Gleadthorpe Research Centre*

Laying hens were housed in a controlled environment cage facility at ADAS Gleadthorpe. There were three banks of cages each three tiers high. Lighting was by tungsten bulbs and the ventilation system operated by the high speed jet principle utilising ridge-mounted extraction fans and automated eaves inlets. The target ambient temperature in the house was 21 °C. The minimum ventilation rate was calculated to supply $1{\cdot}9 \times 10^{-4}$ m^3 [air] s^{-1} $kg^{-0{\cdot}75}$ [lw] and this rate was supplied by one 610 mm fan. Birds were fed by hand, at regular intervals, using troughs, and water was provided by nipple drinkers. Manure disposal was by a belt-clean system beneath each cage tier.

2.1.3. *Laying hens—commercial poultry unit*

At the commercial facility, birds were accommodated in three houses.

(1) The first house contained three-tier cages and manure disposal was by a belt-clean system beneath each tier, with weekly removal of the manure. Ventilation was provided by a reverse-flow system with fans mounted in the side walls drawing air through inlets in the ridge. The fans operated through a thermostatic control system with an interval timer independently operating the minimum ventilation stage.
(2) The second house was of deep-pit design, with manure stored under the house, and similarly contained three-tier cages. Ventilation was of standard design for a deep-pit house having extraction fans sited in the pit walls drawing air through

ridge inlets and through the house floor. Ventilation control was as per the first house.

(3) The third house was of a design known as the 'stilt house', which is essentially a deep pit below the house with the side walls removed to expose the manure to the atmosphere. Birds in this house were accommodated in three-tier A-frame cages and ventilation was provided by ridge-mounted fans blowing air through valved slots in the house floor. The valves prevented wind intrusion into the house. The ventilation system operated through a thermostatic panel as in the other two houses.

Lighting was by tungsten bulbs in all three houses and feed was provided *ad libitum* in troughs supplied by an automated chain feeder and water was provided by nipple drinkers mounted in the cages.

2.2. *Techniques for measuring ammonia losses from poultry housing*

At the start of the project, a study was undertaken to establish whether acid traps (Lockyer, 1983) or diffusion tubes (Hargreaves & Atkins, 1987) were the most suitable methodology for measuring ammonia losses from broiler and laying hen housing.

The techniques were tested in the broiler house and laying hen house at ADAS Gleadthorpe in August and September 1998. Acid traps and diffusion tubes (in sets of four) were positioned at air outlet points to measure ammonia concentrations in the air leaving the housing, and at air inlet points to measure ammonia concentrations in the air entering the housing. In the broiler house, five acid traps and four sets of diffusion tubes were placed next to the air outlets, with three acid traps and one set of diffusion tubes in the corridor outside the room (the air inlet point). In the laying hen house, one acid trap and one set of diffusion tubes were placed next to each of four extractor fans and on the outside of the house (the air inlet point).

The acid traps consisted of test tubes containing 30 m*l* of 0·02 M orthophosphoric acid (to adsorb ammonia). These were connected to pumps that bubbled air through the acid before it entered or left the house. The pumps were fitted with metres to measure the flow rate and total volume of air passing through the acid traps, allowing the quantity of ammonia adsorbed by the acid to be calculated. The diffusion tubes consisted of a 7 cm length of polytetrafluoroethylene (PTFE) tubing of approximately 1 cm diameter. Ammonia collection was by adsorption onto 1 cm diameter glass microfibre discs saturated with 0·1 M sulphuric acid, held in place at one end with a coloured polythene cap. The other end of the tube was sealed with a clear cap after the tube had been prepared which was removed at the start of the exposure period.

Ammonia gas cylinders were used to release known quantities of ammonia into the houses. The cylinders were fitted with gas meters to measure the gas flow rate during the tests. Even distribution of ammonia throughout the building was ensured by using a fan to blow it through a network of perforated polythene tubing (approx. 50 cm diameter) laid on the floor of the houses. Measurements were made for approximately 22 h. Six test runs (three in each house) were conducted to simulate different environmental conditions. Ventilation rates ranged from 0·2 to $1{\cdot}2\,m^3\,s^{-1}$ and ammonia concentrations from 5 to $10\,mg\,l^{-1}$ in the broiler housing, whereas ventilation rates ranged from 0·3 to $12\,m^3\,s^{-1}$ and ammonia concentrations from 4–$8\,mg\,l^{-1}$ in the laying hen housing.

2.3. *Ammonia losses from broiler litter and laying hen manure management systems*

In both Experiments 1 and 2 described below, day-old broiler chicks (600 male and 600 female; stocking density $14{\cdot}3\,birds\,m^{-2}$) were housed in each of the eight rooms in the climate facility at ADAS Gleadthorpe.

2.3.1. *Experiment 1: The effects of different litter types and quantities*

The effects of different litter types and quantities, on ammonia emissions, were studied for broiler flocks reared and housed over 46 days in winter (November 1998–January 1999); and over 43 days in summer (August–October 2000). Each room contained 72 'Aqua 2' nipple drinkers. Two types of litter (straw and woodshavings) were provided at depths representative of current commercial practice (5 cm) and 1.5 times commercial practice (7.5 cm), with two replicates of each litter treatment.

2.3.2. *Experiment 2: The effects of drinker design and litter moisture content*

The effect of different drinker types on ammonia emissions was studied for a broiler flock reared over a 42 day period (January–March 2000). Woodshavings were introduced to an even depth of 5 cm. Two types of drinkers (traditional bell drinkers or nipple drinkers) were provided, with four replicates carried out for each drinker treatment.

2.3.3. *Experiment 3: The effect of laying hen manure removal frequency*

The effect, on ammonia emissions, of different laying hen manure removal frequencies (daily or weekly) from a belt-scraped system was studied in the controlled environment cage facility at ADAS Gleadthorpe. The flock consisted of *ca.* 3500 birds housed in cages of 4–8 birds in three banks of three tiers, with the manure collected on a belt beneath each bank. Measurements of ammonia emissions from each manure removal frequency treatment were made on the first two weeks of alternate months between September 1998 and July 1999. During these two weeks the belts were scraped either daily or weekly, thus allowing seasonal variations in ammonia losses from the housing from each treatment to be studied. Whilst ammonia measurements were not taking place, the belt was scraped weekly.

2.3.4. *Experiment 4: Ammonia losses from a commercial laying hen unit*

Ammonia losses from three different laying hen housing systems (belt-scraped, deep-pit and stilt house) were measured on a commercial laying hen unit (described above), between April 2000 and March 2001. There were *ca.* 20 000 birds in both the belt-scraped and deep-pit houses, and *ca.* 25 000 birds in the stilt house.

2.4. *Measurement of ammonia losses from different stages of the manure management continuum*

2.4.1. *Housing*

Continuous measurement of ammonia emissions from the broiler and laying hen houses at ADAS Gleadthorpe was made using the acid trap methodology, which was seen to be the most appropriate method of measuring emissions in poultry housing (see Section 3.1). The volume of air entering each room in the broiler house and the whole of the laying-hen house was monitored continuously using data loggers connected to the fans. The volume of acid in the acid traps was checked daily and topped up with deionised water as necessary, with the samples analysed for NH_4-N using standard methods (MAFF, 1986).

In the broiler housing (Experiments 1 and 2), one acid trap was installed near the air outlet in each of the eight rooms, with an additional two acid traps in the building corridor near to the fans to measure ammonia concentrations in the inlet air. The acid in the acid traps was changed twice a week, except at the end of the rearing period when the acid was changed to cover the time period between the broilers being removed from the rooms and the end of litter removal.

In the laying hen housing (Experiment 3), eight acid traps were installed at different positions in the house and three outside the house to measure ammonia concentrations in the inlet air. The acid in the acid traps was changed at the end of the weekly monitoring periods, except during March 1999 when it was changed every day to provide an indication of daily ammonia losses.

At the commercial laying hen unit (Experiment 4), housing ammonia concentrations were measured using diffusion tubes as it was impractical to install acid trap monitoring equipment. Seven sets of diffusion tubes (four tubes per set) were placed near to the air vents in the belt-scraped and deep-pit houses, and underneath the floor of the stilt house immediately above the manure (outlet air samples). A set of tubes was also placed on the perimeter of the housing area to measure background ammonia concentrations on the unit (inlet air samples). The tubes were exposed for approximately 24 h. Measurements were made at approximately two monthly intervals to provide a total of seven datasets over the period (May 2000–March 2001). The results were corrected for incomplete recovery using the ammonia recovery efficiency measured for diffusion tubes in laying hen housing study (see Section 2.2).

2.4.2. *Manure transport and storage*

Broiler litter and laying hen manure (Experiments 1–3) were moved from the building to field storage heaps using a large walled trailer. Masts were erected on each wall of the trailer and pairs of Ferm tubes (Ferm *et al.*, 1991) were attached at heights of 0·2, 0·5 and 1·0 m above the sides of the trailer to measure ammonia emissions. In Experiment 4, laying hen manures removed from the commercial unit were transported to ADAS Gleadthorpe in covered lorries, although ammonia losses were not measured during transport. Representative samples of all the manure types were taken on removal from the houses and analysed for dry matter, total N, NH_4-N, NO_3-N, uric acid-N, total organic carbon and pH, using standard methods (MAFF, 1986).

The broiler litter (Experiments 1 and 2) was stored for 6–12 months in field heaps (one per room), each containing around two tonnes of litter. In Experiment 3, four layer manure heaps of *ca.* 6–8 tonnes each were stored for 10–16 months, whilst in Experiment 4, eight layer manure heaps of *ca.* 2 tonnes each were stored for 5 months. The heaps had retaining walls to a height of *ca.* 0·5 m which were lined to provide an impermeable base. Four masts were erected at the side of each heap and pairs of Ferm tubes were attached at heights of 0·2, 0·8 and 2 m above the level of the manure in the heap to provide continuous measurements of ammonia emissions. The Ferm tubes were changed at 2–8 week intervals throughout the 5–16 month storage period. A fresh set of tubes was installed immediately before land spreading and exposed for *ca.* 24 h to measure ammonia losses during heap breakout.

2.4.3. *Land spreading*

The broiler litters and laying hen manures (dry matter, total N, NH_4-N, NO_3-N, uric acid-N, total organic carbon and pH) and soils (moisture content, pH, organic matter, total N, NH_4-N, particle size distribution) were analysed prior to land spreading using standards methods (MAFF, 1986). All manures were spread to arable stubbles at ADAS Gleadthorpe (plot size 12 m by 3 m) at rates supplying a target of 250 kg ha^{-1} total N, the maximum recommended in the Water Code (MAFF, 1998). Broiler litter was spread in January 2000 (Experiment 1—winter housed flock), March 2001 (Experiment 1—summer housed flock) and September 2000 (Experiment 2). Laying hen manure was spread in January 2000 (Experiment 3) and November 2001 (Experiment 4).

Ammonia emissions were measured using the equilibrium concentration technique (Svensson, 1994). Two chambers were placed at random on each plot as soon as possible after the manure was spread, with one ambient sampler placed between the two chambers and the passive diffusion samplers (PDS) placed as close as possible to the manure surface. The position of the chambers was changed between sampling periods to avoid differential manure drying rates. Measurements following land spreading continued for *ca.* 30 days.

2.4.4. *Whole system ammonia-N losses*

For the broilers (Experiments 1 and 2), the measured losses were used to compare ammonia-N losses from each stage of the manure management continuum (housing, storage, land spreading), assuming that all the litter produced was spread to land.

For the laying hens at Gleadthorpe (Experiment 3), annual housing losses were extrapolated from the weekly belt-scraped measurements. Total storage losses (from storage heaps of *ca.* 2 m depth) were calculated from measured emission rates and annual manure production (estimated from excretion rates during the measurement periods). Spreading losses were estimated using the mean ammonia loss following land spreading, after making allowances for a decrease in manure total N and uric acid N plus ammonium-N (UAN) contents during storage. For the commercial unit (Experiment 4), housing losses were calculated using the mean ammonia loss rate measured from the three housing types. Manure production was estimated using a standard excretion rate of 41 t per 1000 birds (Anon, 2000) with a flock size of 20 000 birds. The stored manure was estimated to emit ammonia at the mean measured rate. Spreading losses were estimated as described for broiler litter.

3. Results and discussion

3.1. *Techniques for measuring ammonia losses from poultry housing*

In the broiler housing study, the mean recovery of ammonia gas was 69% for diffusion tubes and 113% for acid traps for the range of ventilation rates (0·2 and 1·2 m^3 s^{-1}) and ammonia concentrations (5 and 10 mg l^{-1}) tested. The standard error (SE) of the measurements was similar for both techniques at *ca.* 5%.

Similarly in the laying hen housing study, the mean recovery of ammonia gas when ventilation rates were medium/high (4·1 and 12·0 m^3 s^{-1}) was *ca.* 77% for diffusion tubes and *ca.* 108% for acid traps. The SE of the measurements was similar for both techniques (*ca.* 16%). However, the mean ammonia recovery at the low ventilation rate (0·3 m^3 s^{-1}) was poor at only 20–26% for both measurement techniques. Under these conditions natural ventilation of the house can be dominant over the fan ventilation, especially when the weather is windy. This highlights the need to use care when interpreting the results of ammonia loss measurements made during very cold weather from ventilated buildings. However, all the measurements in Experiments 1–4 were undertaken when ventilation rates were $>0·8$ m^3 s^{-1}.

Statistical analysis of the results by analysis of variance confirmed that the diffusion tubes recoveries obtained in the broiler and laying hen housing were significantly (probability $P<0·05$) lower than 100%, whereas the acid trap recoveries were not significantly ($P>0·05$) different from 100%. As the acid trap technique gave good quantitative recoveries, it was selected as the most appropriate method for use in the broiler and laying hen housing studies at ADAS Gleadthorpe (Experiments 1–3).

3.2. *Ammonia losses from broiler systems*

3.2.1. *Housing*

For the winter housed broiler flock (Experiment 1), ammonia losses from broilers on straw (mean 2·0 g [NH_3-N] h^{-1} 500 kg^{-1}[lw]) were higher ($P<0·05$) than for those on woodshavings (mean 1·0 g [NH_3-N] h^{-1} 500 kg^{-1}[lw]). The lower emission rate from birds on woodshavings was considered to be due to the greater amount of bedding dry solids added (a mean of 480 kg woodshavings per room compared with a mean of 275 kg straw per room). For the summer housed flock, mean ammonia losses (*ca.* 2·8 g [NH_3-N] h^{-1} 500 kg^{-1}[lw]) were almost double ($P<0·05$) those from the winter housed flock (mean 1·5 g [NH_3-N] h^{-1} 500 kg^{-1}[lw]) because of higher ventilation rates in the warmer weather (a mean 1·9 $m^3 s^{-1}$ in summer compared with a mean of 0·8 $m^3 s^{-1}$ in winter), with no difference ($P > 0{\cdot}05$) between the litter types. There were no differences ($P > 0{\cdot}05$) in ammonia emissions between the two bedding addition rates (5 and 7·5 cm) for either the winter or summer housed flocks. These results were consistent with those reported by Elwinger and Svensson (1996) where no differences in ammonia emissions from broiler houses were measured from different litter types (straw/wood-shavings) or amounts used.

The design of broiler drinkers had previously been shown to influence the usage of water and broiler litter moisture content (Tucker & Walker, 1992). Wet litter can lead to high ammonia levels in broiler housing (Elliot & Collins, 1982) and may cause bird health problems such as hock burn (Tucker & Walker, 1992). In Experiment 2, ammonia losses from broilers using traditional bell drinkers were greater (mean 3·3 g [NH_3-N] h^{-1} 500 kg^{-1}[lw]) than those using nipple drinkers (mean 1·1 g [NH_3-N] h^{-1} 500 kg^{-1}[lw]), although these differences were not statistically significant ($P > 0{\cdot}05$). In a Swedish study, lower emissions were measured from broilers using nipple drinkers than those using bell drinkers (Elwinger & Svensson, 1996). Similar results were also obtained by Da Borso and Chiumenti (1999) who found that buildings equipped to prevent water dripping onto the litter from nipple drinkers emitted less ammonia (0·40 g day^{-1} $bird^{-1}$) than those with standard design nipple drinkers (0·66 g day^{-1} $bird^{-1}$).

The measured housing ammonia losses were generally within the range of values measured in other UK studies (1·56–6·84 g [NH_3-N] h^{-1} 500 kg^{-1}[lw]) reported in the UK Inventory of Ammonia Emissions (Misselbrook, 2000) and seven Swedish experiments (mean 5·4 g [NH_3-N] h^{-1} 500 kg^{-1}[lw]) reported by Elwinger and Svensson (1996). However, the measured ammonia-*N* losses from the broiler houses in this study represented only *ca.* 3% of total N inputs with feed, which was considerably lower than the proportion (19%) reported by Elwinger and Svensson (1996). Differences in feed protein content and conversion efficiencies, used in the respective studies are considered to be responsible for such a variation.

3.2.2. *Storage and manure handling*

There were no differences ($P > 0{\cdot}05$) in ammonia emissions between the different litter types/rates or drinker treatments during broiler litter storage. Total ammonia losses ranged from 42 to 572 g [NH_3-N] m^{-2} of initial heap surface area and were similar to the ammonia losses measured from uncovered broiler litter heaps stored for 12 months (271 g [NH_3-N] m^{-2}) by Chambers (2001). Covering manures during storage has been shown to reduce ammonia emissions by 60–86% (Chadwick *et al.*, 2002). Ammonia loss rates during litter transport from housing to storage were high (upto *ca.* 750 g [NH_3-N] m^{-2} day^{-1}). However, because the litters were only on the trailer for a few hours, the total amount of N lost represented only 5–8% of the total ammonia-N losses measured during storage. Similarly, ammonia loss rates during heap break-out were up to 6–10 g [NH_3-N] m^{-2} day^{-1}, but accounted for less than 1% of the total ammonia-N losses measured during storage.

The total N content of the manures declined by 45–60% (from 27–30 to 12–16 g kg^{-1}) during storage. Ammonia losses during manure transport, storage and heap break-out accounted for only 4–13% of this decline. It is likely that N would also have been lost by the production of other gaseous N products from microbial respiration and denitrification (*i.e.* N_2O, N_2 and NO_x), although this was not measured.

3.2.3. *Land spreading*

There were no differences ($P > 0{\cdot}05$) in ammonia emissions between any of the broiler litter treatments following land spreading, with total ammonia-N losses equivalent to 46–92% (mean 63%) of the UAN applied over the *ca.* 28 day measurement periods. This was in good agreement with the mean emission factor of 63% for poultry manures reported by Misselbrook (2000) derived from 30 field spreading experiments at various UK sites, although higher than the 35% given as a typical value for poultry manures by Chambers *et al.* (1999) from four earlier experiments. Rapid incorporation of the manures following land-spreading will reduce ammonia emissions (Chambers *et al.*, 1999).

3.2.4. *Whole-system ammonia losses*

Whole system ammonia-N losses ranged from 2·1 to 3·6 kg 500 kg^{-1} [lw] (*Fig. 1*). The winter-housed flock in Experiment 1 had greater losses during the storage phase than the other two experiments, probably because the litter was stored for longer (12 months compared with 6 months). Correspondingly lower losses were measured following land spreading of the broiler litter from the winter housed flock. Data from all three experiments showed that ammonia losses following land spreading and during housing comprised around 57 and 28% of the total system losses, respectively, with losses during storage (including handling and breakout) only accounting for around 15% of total ammonia losses. The UK Inventory of Ammonia Emissions (Misselbrook, 2000) reports the overall balance of losses from poultry housing, storage and land spreading at 51%, <1% and 48% of total system losses, respectively.

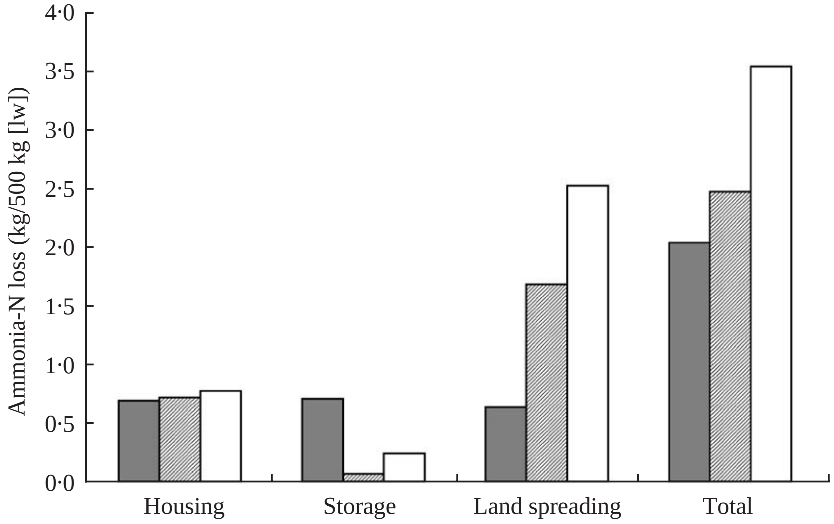

Fig. 1. Ammonia-N losses from each stage of the broiler litter management system: ■*, experiment 1—winter housed;* ▨*, experiment 1—summer housed;* □*, experiment 2—drinker type*

These findings indicate that losses during broiler litter handling, storage and transport were more important than previously thought, although housing and land spreading were still the major ammonia loss routes.

3.3. *Ammonia losses from laying hen systems*

3.3.1. *Housing*

At Gleadthorpe, ammonia losses from the weekly belt-scraped manures (mean 3·3 g [NH_3-N] h^{-1} 500 kg^{-1}[lw]; replication $n=6$) were more than double ($P<0{\cdot}05$) those from the daily belt-scraped measurements (mean 1·3 g [NH_3-N] h^{-1} 500 kg^{-1}[lw]; $n=6$), *Fig. 2*. These results were similar to those from the Netherlands where belt-scraping twice daily reduced ammonia emissions to one-third of the level where the manure was scraped twice weekly (Groot Koerkamp, 1994). In the detailed study at Gleadthorpe (March 1999) during weekly belt-scraping, ammonia emissions increased on the last two measurement days as manure built-up on the belts (*Fig. 3*), which may have been due to an increase in temperature of the accumulating manure on the belt, although this was not measured. This increase in ammonia emissions with increasing amounts of manure on the belt was also reported by Groot Koerkamp *et al.* (1995). These findings indicate that growers with belt-clean systems could reduce ammonia emissions from housing by *ca*. 50% through scraping the belts twice weekly rather than weekly.

Ammonia losses from the laying hen housing were generally higher ($P=0{\cdot}06$) in summer (mean 3·2 g [NH_3-N] h^{-1} 500 kg^{-1}[lw]) than in winter (mean 1·4 g [NH_3-N] h^{-1} 500 kg^{-1}[lw]), because of higher ventilation rates during the warmer summer months (a mean of 8·9 m^3 s^{-1} in summer compared with a mean of 1·4 m^3 s^{-1} in winter). In Italy, Da Borso and Chiumenti (1999) also reported lower ammonia emissions in winter (mean 0·028 g day^{-1} bird^{-1}) than summer (mean 0·154 g day^{-1} bird^{-1}) for laying birds in houses where belts with different manure drying systems were installed.

On the commercial laying hen unit, mean ammonia losses from the deep-pit house (8·2 g [NH_3-N] h^{-1} 500 kg^{-1}[lw]) were greater ($P<0{\cdot}05$) than from the belt-scraped (2·7 g [NH_3-N] h^{-1} 500 kg^{-1}[lw]) and stilt houses (1·4 g [NH_3-N] h^{-1} 500 kg^{-1}[lw]), *Fig. 4*. The higher emission rate from the deep-pit house was most probably because the manure was stored under the house where it remained wet, whereas the manure was removed at weekly intervals from the belt-scraped house and the manure from the stilt house was stored in the open underneath the building where it could dry out. Measured losses from the stilt house may have been lower than the actual emission because of the effect of wind blowing across the exposed manure under the house, which would have removed additional ammonia to that in the air forced through the building by the monitored ventilation system. This suggests that the diffusion tubes would not have captured all the ammonia, although it was not possible to estimate to what extent the results were likely to be an underestimate. The ammonia losses from the belt-scraped house were similar to those measured in Experiment 3 at ADAS Gleadthorpe from the weekly belt-scraping (mean 3·2 g [NH_3-N] h^{-1} 500 kg^{-1}[lw] in summer and 1·4 g [NH_3-N] h^{-1} 500 kg^{-1}[lw] in winter).

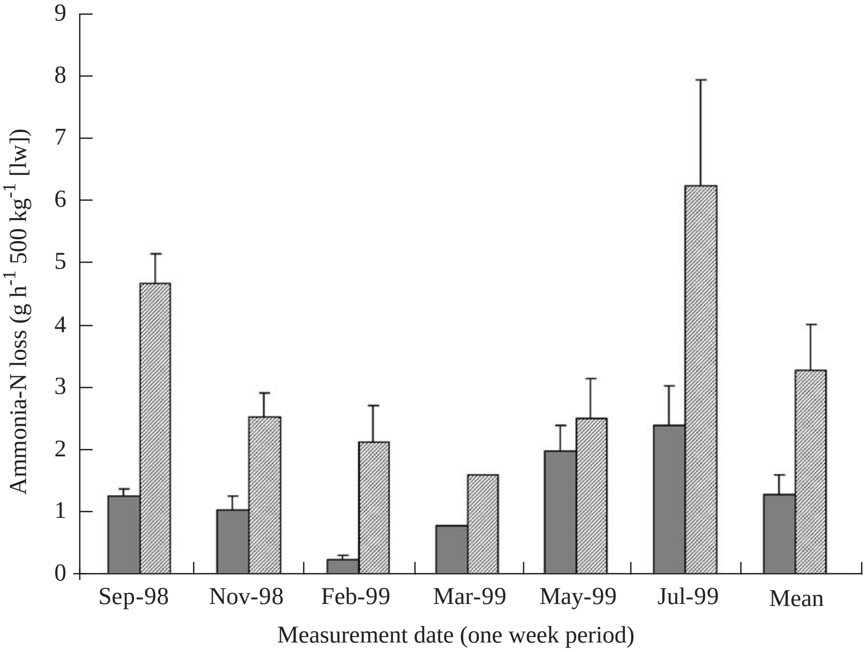

Fig. 2. Ammonia emissions during daily and weekly layer manure belt-scraping (September 1998—July 1999): ■*, daily scraping;* ▨*, weekly scraping*

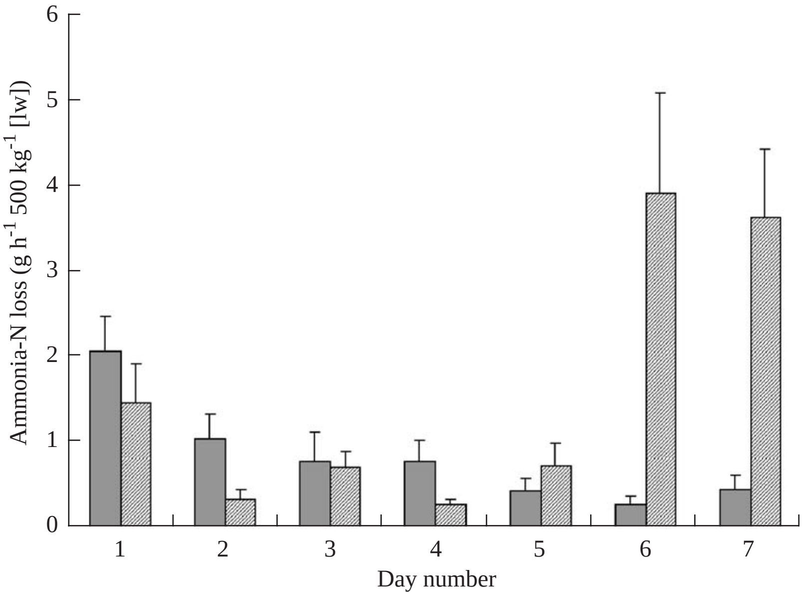

Fig. 3. Daily ammonia emissions during daily and weekly belt-scraping (March 1999): ■*, daily scraping;* ▨*, weekly scraping*

3.3.2. *Storage and handling*

For the Gleadthorpe studies (Experiment 3), total ammonia-N losses over the storage period (5–16 months) were between 508 and 1111 g m^{-2} of initial heap surface area. Ammonia loss rates during handling and heap break out were high (upto 180 g [NH_3-N] m^{-2} day^{-1}). However, because these operations only lasted for a few hours, the total amount of N lost represented only *ca.* 10% of the total ammonia-N losses measured during storage. For the commercial unit (Experiment 4), storage losses from the stilt house, deep-pit and belt-scraped manures were similar (560–764 g m^{-2} initial heap surface area). The losses measured during Experiments 3 and 4 were higher than previously measured

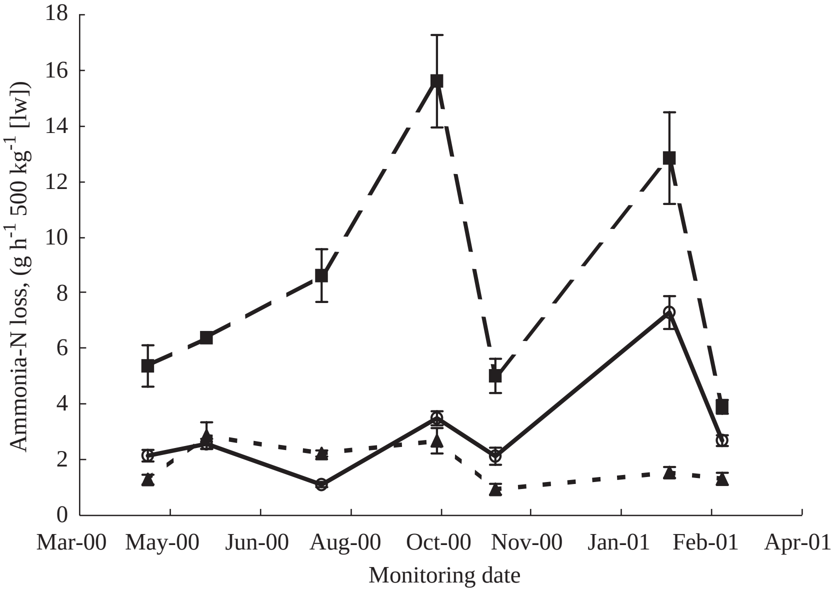

Fig. 4. Ammonia emissions from different housing designs on a commercial laying hen unit (May 2000 – March 2001): ○, belt-scraped; ■, deep pit; ▲, stilt house

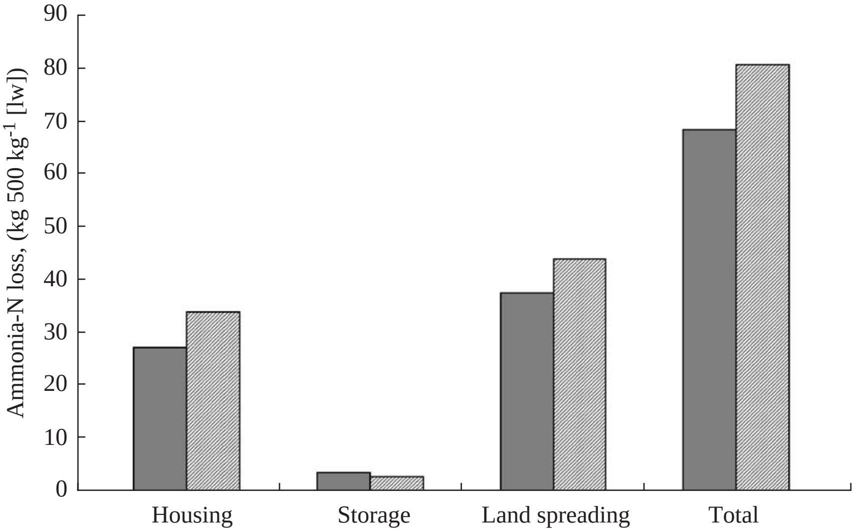

Fig. 5. Ammonia-N losses from each stage of the laying hen manure management system): ■, Gleadthorpe; ▨, commercial unit

during the storage of deep-pit (192 g m^{-2}) and belt-scraped manures (159 g m^{-2}) for 12 months (Chambers, 2001).

The total N content of the manures declined by 19–43% (from 15–19 to 8–16 g kg^{-1}) during storage. Ammonia losses during manure transport, storage and heap break-out accounted for only 16% of this decline. It is likely that N would also have been lost by the production of other gaseous N products from microbial respiration and denitrification (*i.e.* N_2O, N_2 and NO_x), although this was not measured.

3.3.3. *Land spreading*

There were no differences ($P > 0{\cdot}05$) in ammonia emissions following land spreading between the different layer manure removal treatments (Experiment 3) or between layer manures from the different commercial unit houses (Experiment 4), with total NH_3-N losses equivalent to 67–118% of the UAN applied over the 28 day measurement periods.

3.3.4. *Whole system ammonia losses*

For Experiments 3 and 4, a mean of 41 and 55% of total ammonia losses were from housing and land spreading, respectively, with only 4% of losses occurring during manure storage (*Fig. 5*). These results were similar to the overall balance estimates in the UK Inventory of Ammonia Emissions (Misselbrook, 2000) where losses from poultry housing, storage and land spreading make up 51%, <1% and 48% of total system losses, respectively.

4. Conclusions

The results have demonstrated that manure management practices (*e.g.* housing design, frequency of manure removal, drinker and litter types) can be changed in a practical and cost effective way to reduce ammonia losses during poultry housing, but these changes had no measurable effects on ammonia losses during storage or following land spreading. The whole-system ammonia loss measurements indicated that strategies to reduce ammonia emissions from poultry farming would be most effective if focused on housing and land spreading practices, where ammonia losses are the greatest. However, it is important that N conserved during housing should be protected against down stream losses (*i.e.* during storage and following land spreading). Therefore, abatement measures during storage (*e.g.* covering heaps) and following land spreading (*e.g.* rapid incorporation) can also make a valuable contribution to reducing overall ammonia losses from poultry farming.

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