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Ammonia Abatement Strategies in Livestock Production: A Case Study of a Poultry Installation

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Abstract

This study uses a linear programming approach to compare the potential effectiveness of uniform rules (under the Integrated Pollution Prevention and Control Directive) and a landscape-scale based policy for reducing ammonia (NH_3) emissions and their related impacts from a case study poultry installation. The model incorporates a variety of potential NH_3 abatement techniques. It also incorporates the first application of a spatial model of the diffusion of environmental impacts from NH_3 emissions. This models N deposition at a nearby nature reserve. The model finds that the uniform rules proposed under the Integrated Pollution Prevention and Control Directive are likely to be ineffective in certain contexts and that a landscape-scale approach is more suitable for reducing N deposition from livestock production units in environmentally sensitive locations. However, the adjustments required are associated with large reductions in net margin. This reflects the limited range of cost-effective NH_3 abatement techniques available. An alternative cost-effective abatement technique could be to maintain a spatial buffer between poultry production and sensitive receptors.

Keywords: Ammonia, Integrated Pollution Prevention and Control, Broiler installations

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1 *Introduction*

Agricultural activities give rise to significant amounts of air pollutants (Brink *et al*., 2002). Particular concerns have centred on the emissions of ammonia (NH_3) and its environmental impacts (Hornung and Sutton, 1995; Asman *et al*., 1998) and accordingly, policies have been developed that aim to reduce NH_3 emissions. The policies implemented to date have resulted from international agreements with targets being defined at a national level. This is the case, for example with the commitments to bring NH_3 emissions within national ceilings under the Gothenburg Protocol (Gothenburg Protocol 1999, National Emissions Ceilings Directive 1999).

Assessments of the expected effectiveness of these targets set at a national level are being conducted using models at the UK scale with a 5 km resolution (e.g. NEGTAP 2001). This, and recent work on the landscape-scale variability in NH_3 and other atmospheric N compounds (at a 25m resolution) (Dragosits *et al*., 2002, Theobald *et al*., 2004), suggest that existing policies will not succeed in protecting many semi-natural ecosystems, such as forests, moorlands and grasslands.

A policy approach that places the responsibility for adjustment at the firm level and that could operate in a more spatially discriminating way at a local level may be possible under the 1996 Integrated Pollution Prevention and Control (IPPC) Directive, but the approach taken so far for agriculture has focused on developing a modest set of Standard Farm Installation (SFI) rules that should be implemented irrespective of farm location.

There is a need to consider the effectiveness and costs of policies being developed and implemented in regulating site specific N loads. To this end a Linear Programming (LP) model is developed and used in order to compare the potential costs and effectiveness of uniform rules (as currently being implemented under the IPPC Directive) and an alternative approach that could reflect local circumstances at the landscape-scale for a case study poultry installation.

The model used incorporates the first application of the Simple Calculation of Ammonia Impact Limits (SCAIL) model in order to identify the impact of NH_3 emissions from specific agricultural units on a nearby ecosystem. By linking the SCAIL model to the LP model, a cost-effective abatement package can be defined for the installation that will achieve critical loads for N at the nature reserve.

2 Economic model

When analysing the implications of integrating environmental and economic goals, extended economic models are required that include parameters for the environmental effects of the production activities considered. There are two types of economic model available for this purpose, namely, econometric models and optimisation models (Wossink *et al.,* 1992).

Econometric models are unsuitable for ascertaining the effects of environmental restrictions because, although they represent real behaviour, they suffer the disadvantage that it is only past behaviour that is represented (Berentsen and Giesen, 1995). Where the aim is to integrate environmental objectives into farm planning, a model is required where attention is given to technical relations and potential policy approaches for which historic data are not available. To this end, optimisation models such as Linear Programming (LP) are frequently employed (Wossink *et al*., 1992).

LP is advantageous in that it can provide a comprehensive study of complex situations by including a larger range of decision variables than is possible with other farm planning techniques (Barnard and Nix, 1979). Essentially LP uses mathematical rules to solve problems, rather than using economic theory. However, because LP is capable of handling economic concepts, such as opportunity costs and marginal analysis, it has become a key tool in economic and business analysis (Boehlje & Eidman, 1984).

The LP model focuses on a case-study poultry installation[1]. The model can be described using the Drivers-Pressures-State-Impact-Response (DPSIR) framework. The DPSIR framework was developed by the OECD in the 1980s to structure information (Walmsley and Pretorious, 1996). The DPSIR framework takes a systems analysis approach where it is used to create a view of the relations between environmental and human systems. The DPSIR framework is useful because it identifies cause and effect relationships, allowing for the separation of issues through the different DPSIR categories, which are defined as:

- Driving forces are the underlying causes that lead to environmental pressures,
- Pressures affect the state of the environment;
- State refers to the state of the environment in terms of quality of natural resources;
- Impact refers to the effect that a pressure has on the state of a natural resource and on user groups;
- Response relates to the social response via policies, laws, programmes and research.

This system is viewed as circular, where it is recognised that the responses, perhaps in the form of policies can create different driving-forces, pressures, states, impacts and responses (EEA, 1999).

[1] Installation - When referring to all units owned by a company on one farm site, the term "Installation" is used. This is in line with the definition given by the IPPC Directive.

2.1 Drivers

It is assumed that the driver of poultry production at the installation is profit maximisation. To maximise profit, the case study farm manager must find an optimal mix of activities at the farm. The main activity at the installation is broiler production (poultry reared for meat). Broilers are reared in 4 units[2] that make up the installation. Each unit has a different spatial orientation relative to the nature reserve. Hence they have different environmental impacts and are treated as separate activities in the model. Consequently, a farmer can vary stocking densities in unit 1, 2, 3, and 4 independently of each other.

The current method of broiler production is the deep litter system, where the floor is covered with a 7.5-10 cm layer of wood shavings. The model includes three low-NH_3 emitting housing system alternatives, which the farm could implement. These are a Poultry Integrated Management System (PIMS), a tiered floor system and a perforated floor system. A unit can select more than one housing system, as units 1, 2 and 3 comprise 6 sheds[3], and unit 4 comprises 8 sheds. Therefore, the model can select from 20 housing production activities for the whole installation.

End-of-pipe techniques can also be selected to abate NH_3 emissions from the poultry units. These techniques are chemical wet-scrubbers and Zeolite air-scrubbers. Information on NH_3 emissions and net margins from the different housing options and abatement systems, and its sources from where the estimates come from are shown in Table 1.

[2] Unit- Is used to describe a group of poultry sheds located immediately adjacent to each other. Units can vary in the number of sheds they contain (typically 1-8). Separate units are usually spaced widely apart (200m – 1 km) across the whole farm site to minimise the risk of disease spreading to the whole flock.
[3] Shed – is the basic broiler-housing element of a farm, which forms other structural compositions

Table 1 Production techniques, N emissions, net margins and data sources

	NH_3 emissions (kg NH_3-N year)	Net margin £ (1000 bird places)$^{-1}$ year^{-1}
Production system		
Deep litter (baseline system)	66 (From EC 2001)	408 (From Nix 2002)
Poultry Integrated Management system	58 (derived from Robertson, 2002)	408 (From Filmer 2003)
Tiered-floor system assuming 20 years economic life	4 (derived from EC 2001)	53 (assuming 20 years economic lifetime) (derived from EC 2001 and Nix 2002)
Tiered-floor system assuming 10 years economic life	4 (derived from EC 2001)	-28 (assuming 20 years economic lifetime) (derived from EC 2001 and Nix 2002)
Perforated floor system assuming 20 years economic life	(derived from EC 2001)	34 (assuming 20 years economic lifetime) (derived from EC 2001 and Nix 2002)
Perforated floor system assuming 10 years economic life	(derived from EC 2001)	-74 (assuming 20 years economic lifetime) (derived from EC 2001 and Nix 2002)
End-of-pipe technique	**NH_3 emissions (kg NH_3-N year)**	**Abatement cost (£/year)**
Chemical-wet scrubbers used with deep litter system assuming 20 years economic life	41 (derived from EC 2001)	-704 (derived from EC 2001)
Chemical-wet scrubbers used with deep litter system assuming 10 years economic life	41 (derived from EC 2001)	-589 (derived from EC 2001)
Chemical-wet scrubbers used with PIMS assuming 20 years economic life	36 (derived from EC 2001)	-704 (derived from EC 2001)
Chemical-wet scrubbers used with tiered-floor system assuming 10 years economic life	36 (derived from EC 2001)	-704 (derived from EC 2001)
Chemical-wet scrubbers used with tiered-floor system assuming 20 years economic life	36 (derived from EC 2001)	-589 (derived from EC 2001)
Chemical-wet scrubbers used with perforated floor system assuming 20 years economic life	36 (derived from EC 2001)	-589 (derived from EC 2001)
Chemical-wet scrubbers used with Perforated floor system assuming 10 years economic life	(derived from EC 2001)	-704 (derived from EC 2001)
End of Pipe Technique	**NH_3 reduction (kg NH_3-N year)**	**Abatement cost** (£ **kg NH_3-N^{-1} year^{-1})**
Zeolite air-scrubbers in all system	1 (From ADAS, 2000)	39 (From ADAS, 2000)

Note: Units 1, 2 and 3 have an economic life of 10 years as they are older and unit 4 has an economic life of 20 years as this is relatively new.

A by-product of broiler production is manure, which can be sold as fertiliser to farmers or as fuel to a nearby power station. This activity is separate from the sale of birds and also generates revenue independently. The value received from the manure for incineration is dependent on its dry matter content. Table 2 describes the net margin for manure in each activity and how this varies according to its dry matter content.

Table 2 Net margin for manure according to its dry matter content

Manure Dry Matter content	Value of manure tonne^{-1} FM (£)
80% plus	6.96
70-75%	5.70
60-65%	4.44
50-55%	2.60
Manure sold as fertiliser (value is not dependent on dry matter content)	3

Note: The value for manure sold for incineration includes an ash content adjustment: Manure with less than 22% ash would receive 100% of the above price, manure with more than 31% ash would receive nothing, with progressions in between.

Thus, the objective function of the model can be described as:

$$MAX\sum_{j=1}^{4}\sum_{i=1}^{4}\left[\left(P_b * x_{ij}\right)+\left(P_{(m)h} * m_h * x_{ij}\right)+\left(P_{(m)s} * m_s * x_{ij}\right)+\left(P_{(m)f} * m_f * x_{ij}\right)\right]-\sum_{k=1}^{3}A_k$$

Where j = production system 1,…, 4; i = poultry units 1,…,4; P_b = net margin from poultry production (£ (1,000 bird places)$^{-1}$ year^{-1}); x_{ij} = poultry production (1,000 bird places); $P_{(m)h}$ = net margin from manure sold for incineration with a high dry matter content; (£ tonne^{-1} manure fresh mass); m_h = Quantity of manure with a high dry matter content from system, sold for incineration from system $_j$ (tonnes manure fresh mass (1,000 bird places)$^{-1}$ year^{-1}); $P_{(m)s}$ = net margin from manure sold for incineration with a standard dry matter content (£ tonne^{-1} manure fresh mass); m_s = Quantity of manure with a standard dry matter content from system, sold for incineration from system $_j$ (tonnes manure fresh mass (1,000 bird places)$^{-1}$ year^{-1}); $P_{m(f)}$ = net margin of manure sold for fertiliser (£ tonne^{-1} manure fresh mass); m_f = Quantity of manure with a standard dry matter content from system, sold for fertiliser from system $_j$ (tonnes manure fresh mass (1,000 bird places)$^{-1}$ year^{-1}); A = cost of N abatement (£ year^{-1}); $_k$ = abatement system 1,…,3.

The objective function is subject to several constraints. For instance, each unit has a maximum capacity (dictated by welfare regulations) for rearing birds, which varies from unit to unit. Units 1, 2 and 3 each have a capacity constraint of 150,000 broiler places and unit 4 264,000 broiler places. The constraints for production in each unit are expressed below:

$$x_{ij} \leq C_i$$

where:

C_i = Capacity of unit $_I$ (1,000 bird places)

Bird production can never be negative, therefore, there is a non-negativity constraint on bird production.

$$x_{ij} \geq 0$$

The model also has constraints pertaining to the use of manure. Rearing birds leads to an accumulation of manure, which is removed from the sheds at the end of every production cycle. The farm survey found that the poultry installation could only sell a maximum of half of its baseline manure production to the power station, which is thus modelled as a production constraint:

$$\sum_{i=1}^{4}\sum_{j=1}^{4} \left(m_h * x_{ij}\right) + \left(m_s * x_{ij}\right) \leq Q$$

where:

Q = Manure incineration quota given by the power station (tonnes manure fresh mass year^{-1})

The sale of manure as fertiliser is unconstrained, as it is possible to sell 100% of manure as fertiliser. The model is constrained so that all manure produced must be used in some way; no manure can remain unaccounted for. This takes the form of an equality constraint:

$$\sum_{i=1}^{4}\sum_{j=1}^{4} \left(m_h * x_{ij}\right)+\left(m_s * x_{ij}\right)+(m_f * x_{ij}) = S$$

Where: S = Manure produced by unit (tonnes fresh mass year^{-1})

Manure is sold to the power station at either a lower or higher premium depending on its dry matter content. A transfer row ensures that only manure from low NH_3 emitting housing systems qualifies for sale at a higher premium. This is expressed as:

$$\sum_{i=1}^{4} m_h * x_{ij} \leq S_{ih}$$

Where: S_{ih} = Quantity of manure sold for incineration at a premium price (tonnes manure fresh mass year^{-1})

2.2 Pressures

In the model, the NH_3 emissions from the installation exert pressures on the environment. The adverse environmental impacts are described by Asman *et al*., 1998; Sutton *et al*., 1993; Grantz *et al.,* 2003; Ulrich *et al*., 2002 and Sutton *et al*., 2001. The installation will also emit nitrous oxide (NO) and through the utilisation of its manure at the power station and agricultural fields, will release amounts of nitric oxide (NO) and nitrate (NO_3^-). These losses are not included in the model to reflect the restriction of IPPC regulation to the environmental impacts of the installation itself but will be covered in a future paper.

2.3 State

The land-use in the surrounding area ranges from intensive farmland (arable and pasture) and forests (monoculture and mixed), to semi natural areas of grassy heath. The case study installation is located in close proximity to all three of these land types and is situated next to a nature reserve designated as a Site of Special Scientific Interest (SSSI) for its patchwork of different heaths, mixed woodland, lakes, and wetlands, supporting a variety of rare flora and fauna.

The environmental impacts of NH_3 are spatially variable, deposition being greater, the shorter the distance between source and receptor. Agricultural ecosystems emit and are subject to NH_3 deposition. However, NH_3 is more readily deposited on semi-natural ecosystems, because they are nutrient poor (Sutton *et al*., 2000) and therefore the bulk of deposition and damage occurs in these ecosystems. This highlights the need for the LP model to deal with the site-specific nature of NH_3 emissions from the poultry installation. To achieve this, the LP model links emissions of NH_3 from each unit to the deposition that is likely to occur on sensitive ecosystems near the farm site, as represented by the nature reserve.

To represent this relationship, the LP model incorporates linear coefficients from the Simple Calculation of Ammonia Impact Limits (SCAIL) model developed by the Centre of Ecology and Hydrology (CEH) (Theobold and Sutton, 2001). This is an empirical model that estimates the impacts of NH_3 from agricultural sources at the landscape scale. The model recognises that the amount of NH_3-N deposited on the nature reserve is a function of the distance between the unit and the sensitive receptor, its direction, the volume of emissions, and land cover between farm and the receptor ecosystem. These are all thus input parameters of the SCAIL model. In this study the emission data were obtained from a literature review, the direction of the unit and measurements of distances were taken from ordnance survey maps, whilst a further site walkover in 2003 was used to define the receptor ecosystem and the intervening land cover between the farm and receptor. The data are summarised in Table 3.

Table 3 Unit characteristics, N emissions and deposition data for all farm units in the case study installation

Unit number	Direction of unit from nature reserve (degrees)	Distance from unit to nature reserve (m)	NH_3-N emissions from unit kg yr^{-1}	Land cover between unit and ecosystem	Nature of sensitive receptor	NH_3-N deposition at nature reserve (kg yr^{-1})	NH_3-N deposition from unit to the nature reserve (%)
Unit 1	300	865	9882	Woodland	Woodland	1.920	0.18
Unit 2	324	513	9882	Agricultural	Woodland	6.700	0.63
Unit 3	336	1150	9882	Agricultural	Woodland	1.480	0.14
Unit 4	346	1900	17392.32	Agricultural	Woodland	0.525	0.05
Total			47038.32			10.6247	

2.4 Impact

A baseline run of the model was undertaken to determine the impact of N emissions from the installation on the local environment in the absence of N reduction measures. The production strategy at the installation in the baseline scenario is to produce at capacity using the deep litter system. This was associated with NH_3-N emissions of 47,038 kg NH_3-N $year^{-1}$ and a total net margin of £343,041 $year^{-1}$.

In the baseline scenario N deposition at the nature reserve from the installation was approximately 11 kg N ha^{-1} $year^{-1}$. Critical loads are used in order to determine whether excess N is being deposited on this ecosystem. A critical load is defined as, “a quantitative estimate of exposure to one or more pollutants below which significant harmful effects on sensitive elements of the environment do not occur according to present knowledge” (UNECE 1999 Gothenburg protocol).

The critical load of N for the case study nature reserve (mixed woodland ecosystem) is set by the UNECE at 12.5 kg N ha $^{-1}$ year $^{-1}$ (Sutton *et al*., 2003). However, in order to keep total N deposition beneath the critical load, it is necessary to quantify total current N deposition levels on the nature reserve from all sources, including background deposition. National maps of deposition have been estimated by NEGTAP (2001) and are available through the Air Pollution Information System (APIS), developed at the Centre of Ecology and Hydrology.

APIS holds N deposition data for the whole of the UK. From this it is estimated that the current deposition (including deposition from the case study installation) on the nature reserve is 30.24 kg N ha^{-1} year^{-1} according to NEGTAP (2001). This was comprised of the following elements:

- Wet NO_3 deposition – 3.36 kg NO_3-N ha^{-1} year^{-1}
- Wet NH_4 deposition – 4.48 kg NH_4-N ha^{-1} year^{-1}
- Dry NO_2 deposition – 1.26 kg NO_2-N ha^{-1} year^{-1}
- Dry NH_3 deposition – 21.14 kg NH_3-N ha^{-1} year^{-1}

This figure is well above the critical load for N deposition on mixed woodland, with the largest contribution coming from dry NH_3 deposition. It is therefore likely that the installation would need to reduce its N emissions in order to meet critical load for the nature reserve.

3 Response

The nature reserve is thus receiving excessive amounts of N deposition. Therefore, a policy response is required. This paper identifies and analyses two possible responses. The first strategy operates through the implementation of the Integrated Pollution Prevention and Control Directive (IPPC), the second being the uses Significant Contribution Limits (SCLs; discussed in more detail in Section 4) in order to set ceilings on acceptable deposition levels at the nature reserve.

3.1 Response: Integrated Pollution Prevention and Control Directive

The Pollution Prevention and Control regulations 2000 (PPC) transpose the IPPC Directive into UK law. PPC is already in place to control pollution from new poultry installations, but will not be imposed on existing units until 2006-2007 (Angus *et al*., 2003). It is likely that the PPC regulations will be applied using General Binding Rules (GBRs), a standard set of statutory conditions applying to the entire operation of an installation. GBRs potentially provide a simplified framework within which intensive livestock producers may apply for a permit under the PPC regulations. Although GBRs apply to many pollutants arising from poultry installations, this analysis focuses specifically on the measures controlling NH_3.

Presently there are no formal GBRs for poultry production in the UK; pending this, the EA has developed Standard Farming Installation rules (SFI rules), which will support a simple permitting regime that can be operated in a similar way to GBRs (EA, 2000).

The main emphasis of the SFI rules is to keep the litter within poultry units as dry as possible. The EU BREF document (EC, 2001) describes new low emission housing developed in the Netherlands, which aims to minimise the moisture content of the litter (known as the VEA system, the Dutch abbreviation for broiler low emission). However, the most reliable measurements available have shown that VEA systems do not achieve NH_3 emissions significantly different from those from traditional housing, which uses deep litter flooring, concrete or wood sidewalls, with natural lighting and natural ventilation (EC, 2001; Roger Phillips, SRI; personal communication, 2002). Thus, as there are no discernable differences between fan and naturally ventilated housing the VEA system is not considered to be different from the deep litter system as represented in the LP model.

SFI rules also cover feed protein content. Diets must be formulated to minimise the amount of N excreted by the broilers over the rearing cycle, by optimising crude protein input and feed utilisation. To achieve this, the SFI rules require that birds reared for less than 56 days shall be fed a three/four-phase diet. In fact, the SFI nutritional rules are effectively standard practice in the poultry industry. Typically, broilers are fed a series of diets (three to four) decreasing in protein content through to slaughter, that change with the broilers' nutritional requirements over their life span (personal communication, David Filmer; FLOCKMAN systems; 2003). Taking this view of nutritional controls under the SFI rules, then no change is required from current practice under the PPC regulations. However, the LP model will take the interpretation that the SFI rules do require some element of nutritional management beyond the typical standard and test the use of a Poultry Integrated Management System (PIMS). This approach is taken to determine the maximum effectiveness of the SFI for reducing the impact of NH_3.

3.1.1 The imposition of the SFI rules in the case study poultry installation

The PIMS was forced into the LP solution, to ensure its selection in each unit. The results of this run of the model suggested that profit from the unit would be equal to the baseline model, as a PIMS is associated with approximately the same profit levels as the deep litter system (as shown in Table 1). The emissions associated with this production strategy are 41,693 kg NH_3-N year. Figure 1 compares the NH_3 emissions of the installation under SFI rules with the baseline scenario.

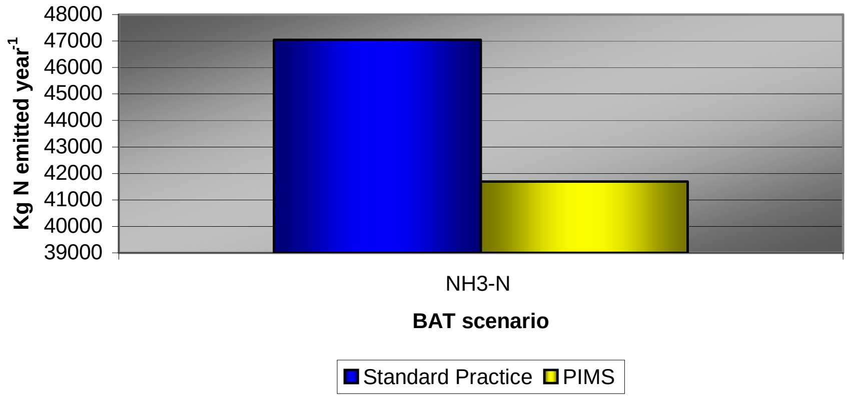

Figure 1 **Comparison of N emissions under SFI rules and baseline scenarios**

Figure 1 shows that both NH_3-N emissions would be reduced by 9% as compared to the baseline scenario. The reduction of NH_3-N emissions is facilitated by a reduced bird N intake, under the PIMS. This could indicate that some N reductions can be made at minimal cost under the IPPC Directive, provided that installations were required to operate a PIMS. Therefore, we should note that the effectiveness of the Directive is dependent on the interpretation of the dietary SFI rules.

Although NH_3-N emissions are lower in the SFI scenario than under the baseline, deposition at the nature reserve would only be reduced by approximately 1 kg NH_3-N ha^{-1} $year^{-1}$. Section 2.4 indicated that deposition at the nature reserve was approximately 30 kg N ha^{-1} $year^{-1}$ and it is unlikely that a 1 kg NH_3-N ha^{-1} $year^{-1}$ reduction would significantly reduce eutrophication. This would suggest that an alternative approach to NH_3 abatement is required at this particular case-study site.

3.2 Emission reductions required to meet critical loads of N deposition

In the absence of statutory guidance targeting achievement of critical loads, this study investigated the idea of using Significant Contribution Limits (SCLs).

SCLs are an emission limit imposed on a source, which will restrict N deposition to a predefined percentage of the critical load. This constraint is modelled as:

$$\sum_{i=1}^{4}\sum_{j=1}^{4} d_{ij} * x_{ij} \leq D_{scl}$$

Where: d = the response of atmospheric N deposition to nature reserve to bird production at a specified distance and direction from the case study installation (kg N ha^{-1} year^{-1} (1,000 bird places)$^{-1}$) from the case study installation; D_{scl} = Significant contribution limit for N deposition at the nature reserve (kg N ha^{-1} year^{-1}).

The case study LP solves the problem for a range of constraining SCLs from 11 kg NH_3-N ha^{-1} year^{-1} to 0.625 kg NH_3-N ha^{-1} year^{-1} (92% and 5% of the critical load respectively), as it is assumed that a poultry unit would be unlikely to be capable of reducing emissions below this level. Figure 2 illustrates the emissions of NH_3-N associated with achieving each SCL, whilst the total net margins associated with meeting these targets are shown in Figure 3.

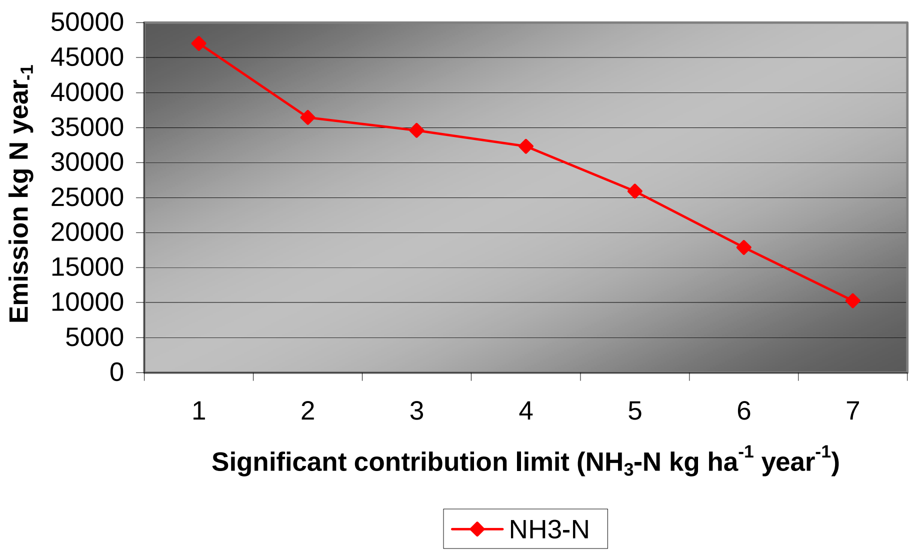

Figure 2 **Emissions of NH_3-N associated with the poultry installation achieving a range of significant contribution limits for the deposition of NH_3-N on the nature reserve**

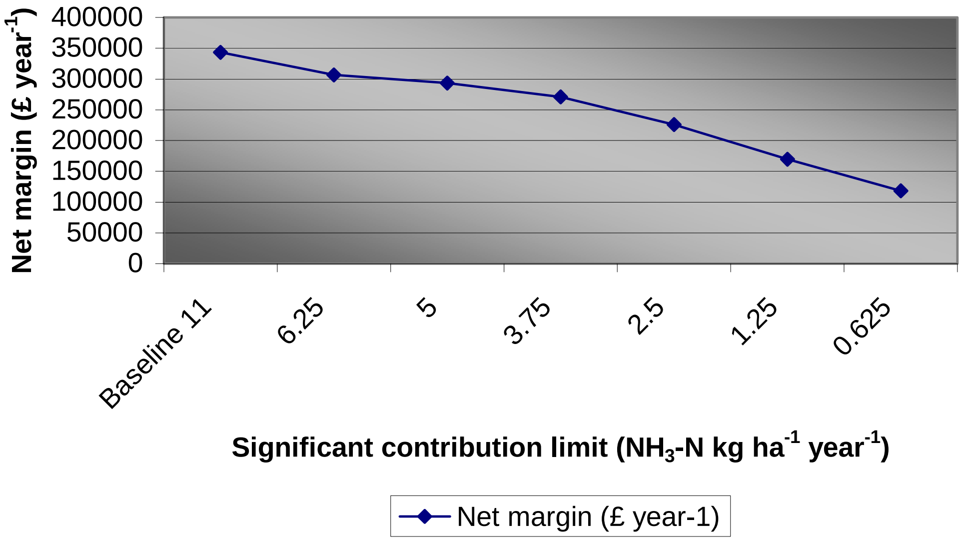

Figure 3 **The cost (in terms of net margin not achieved) of meeting a range of significant contribution limits for the deposition of NH_3-N on the nature reserve**

It is apparent that the total net margin from the installation is closely related to the NH_3-N emissions and the deposition limit. In order to understand how the reductions in NH_3-N deposition are achieved and the subsequent effect on net margin, it is necessary to review which production techniques were employed, as these techniques affect both the level of emissions and net margin. Figure 4 summarises the techniques used at different SCLs.

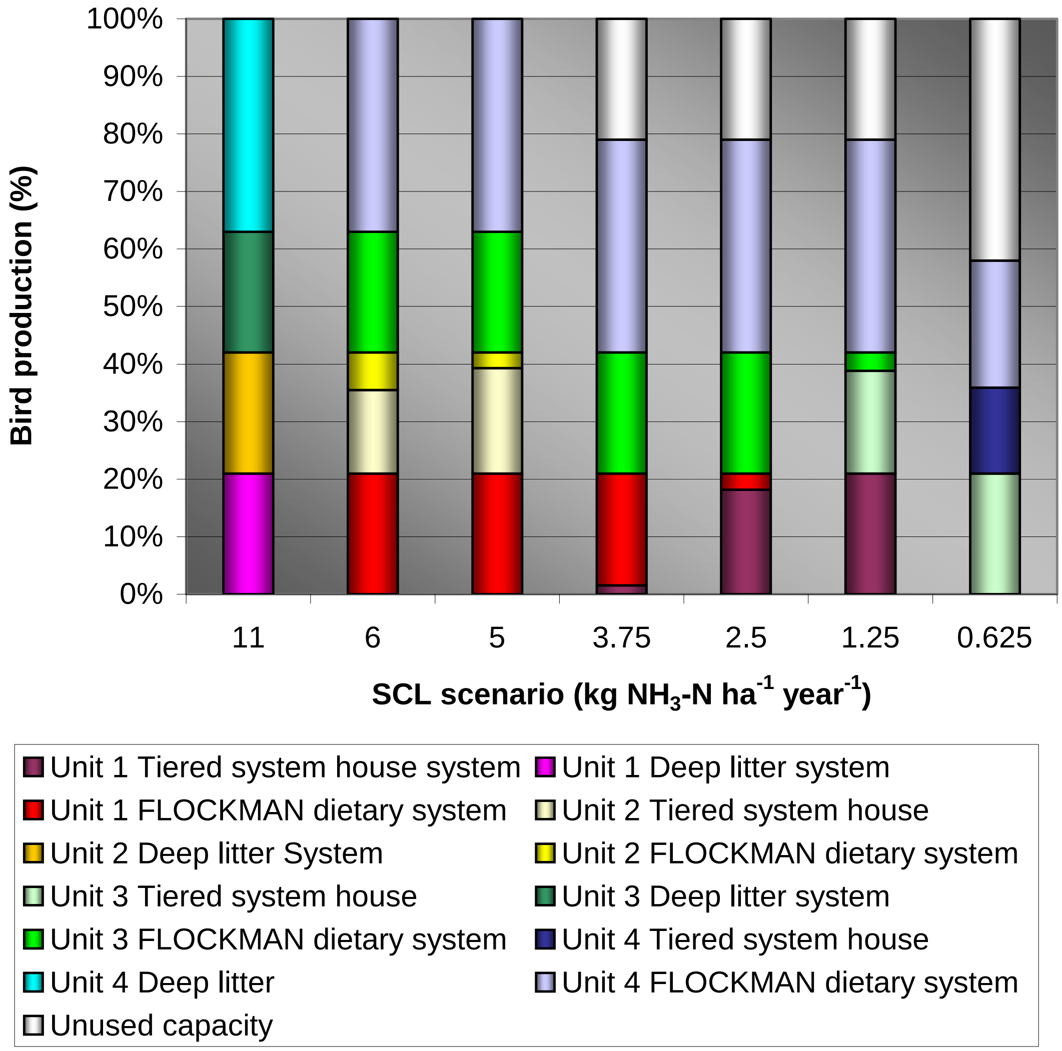

Figure 4 Optimal production strategies at each unit under varying significant contribution limits of NH_3-N as determined from the LP model. Note that the SCL of 11 kg N ha^{-1} $year^{-1}$ represents the baseline scenario at the installation

Up to the 11 kg NH_3-N ha^{-1} $year^{-1}$ SCL, all units rear birds on deep litter. However, as can be seen from Figure 4, once the NH_3-N SCL deposition is reduced to 6 kg NH_3-N ha^{-1} $year^{-1}$ the installation alters its production pattern. Units 1, 3 and 4 switch to using a PIMS, whilst unit 2 produces 103,000 broilers using the tiered floor system and 47,000 using a PIMS. The steady decline in total net margin between these SCLs, indicates that the tiered floor system is gradually being phased in, replacing the PIMS. The production strategy remains similar as the SCL is reduced to 5 kg NH_3-N ha^{-1} $year^{-1}$ it can be observed that the production strategy is similar except the proportion of birds produced on the tiered floor system in unit 2 has increased to 130,000 broilers $year^{-1}$.

When the SCL is reduced to 3.75 kg NH_3-N ha^{-1} $year^{-1}$, the LP results show that production from unit 2 (the unit closest to the nature reserve) stops. The effect of closing unit 2 can also be seen in Figure 3, where total net margin begins to decline more rapidly. Although, production under the tiered floor system remains profitable in this unit, the NH_3-N produced would exceed deposition targets. Unit 1 employs the tiered floor system to rear 10,000 birds with the remaining 140,000 broilers reared on the PIMS. Production in units 3 and 4 is still undertaken using the PIMS.

The production strategy remains fairly stable as the SCL is reduced further from 3.75 kg NH_3-N ha^{-1} $year^{-1}$ to 1.25 kg NH_3-N ha^{-1} $year^{-1}$, where production in unit 1 is carried out entirely on a tiered floor system (150,000 broilers), unit 3 produces 127,000 birds on the tiered floor system and 23,000 broilers under the PIMS whilst 264,000 birds are produced using a PIMS in unit 4. Under a deposition restriction of 0.625 kg NH_3-N ha^{-1} $year^{-1}$, production in the installation ceases at unit 1 and is limited to unit 3 (rearing 150,000 broilers on a tiered floor system) and unit 4 (rearing 106,000 birds on a tiered floor system and 158,000 broilers using a PIMS).

From Figure 4 it can be seen that the LP model uses three strategies to meet deposition targets set for the installation. These strategies are:

- Use of a PIMS,
- Use of the tiered floor system,
- Spatial distancing of broiler production.

There is an intuitive explanation to using these strategies to reduce NH_3-N deposition. Initially, when a restraint is attached to N deposition at the nature reserve, the model will opt to apply a PIMS to units rather than deep litter as it emits less NH_3, for approximately the same net margin level. If further restraints are then placed on deposition, the model adopts the tiered floor system as this is less profitable than a PIMS but emits lower levels of NH_3. When the SCL becomes more restrictive, the model reduces production in the units closest to the nature reserve, which will deposit the most NH_3-N.

This strategy was emphasised by the reduced cost for each activity included in the LP model. The reduced cost can be defined as the increase in the bird price or the reduction of the cost of a system required for an activity to enter the optimal solution (Pannell, 1997). Figures 5 and 6 highlight the reduced cost of the four housing systems. Where a technique has a non-zero value this indicates that it is not included in the optimal solution.

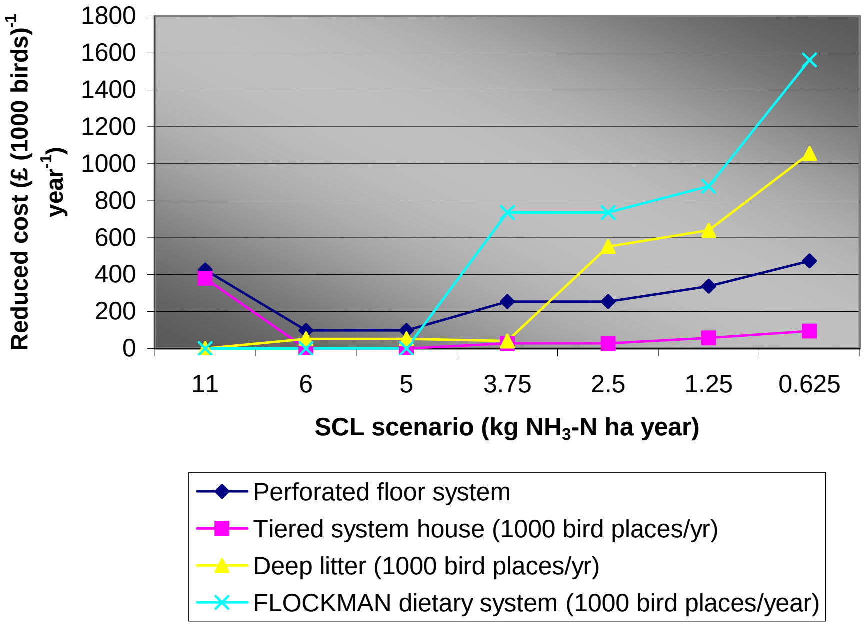

Figure 5 Reduced cost of housing production systems in unit 2 at varying significant contribution limits

Figure 5 shows that initially the deep litter system is used, but is removed from the optimal solution as soon as there is a restriction on NH_3 deposition. The reduced cost of tiered-floor production then decreases as the SCL tightens until it enters the solution with a PIMS. Eventually the deposition target is too restrictive and production from unit 2 ceases, which can be seen from the fact that all housing systems have non-zero reduced costs. Comparing Figures 5 and 6 illustrate the use of spatial distancing of production as an abatement technique.

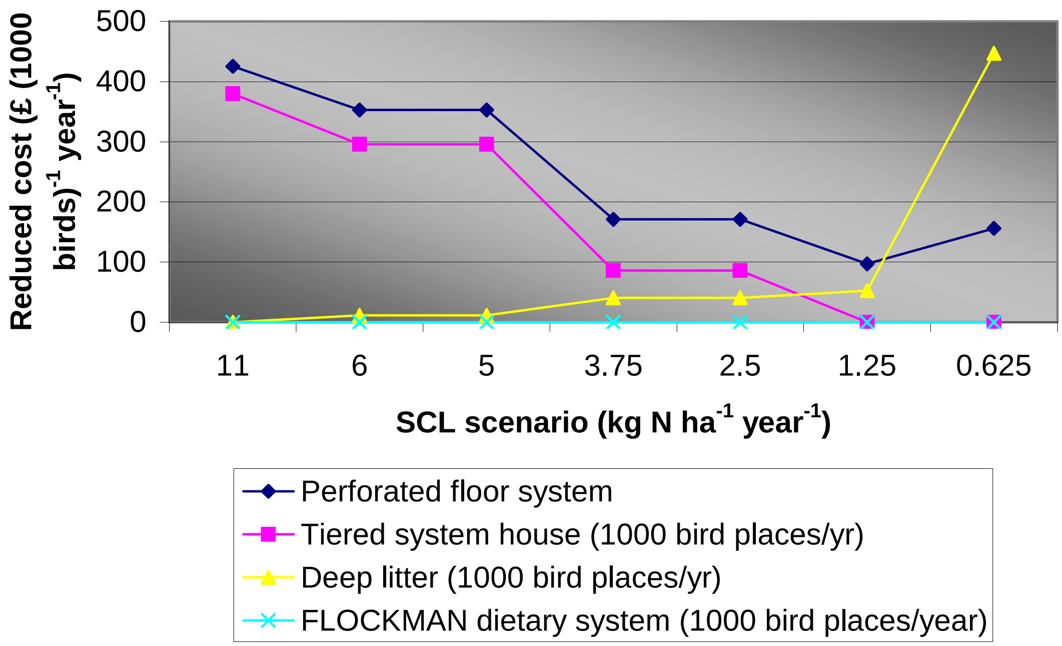

Figure 6 Reduced cost of housing production systems in unit 4 at varying significant contribution limits

The reduced cost of a PIMS is zero throughout the scenarios (indicating it is the selected production technique), with the tiered floor system becoming zero at an SCL of 1.25 kg NH_3-N ha^{-1} $year^{-1}$. Production is maintained in unit 4, at stricter deposition limits than at unit 2 because it is approximately 1,387 metres further away from the nature reserve and therefore deposits less N. A further point to note from Figures 5 and 6 is that the perforated floor system does not enter the solution under any of the assumptions tested. The reduced cost of this system is always higher than that of the tiered floor system, which is capable of achieving greater NH_3 abatement at lower cost. This was also the case for chemical wet scrubbers and zeolite air scrubbers. These were available in the model, but none were included in an optimal solution for any SCL, because they were not financially viable.

4 Sensitivity analysis

A sensitivity analysis was undertaken to determine how the optimal production strategies at the installation would change under different prices received for broilers and manure. The solution for the IPPC Directive was not sensitive to market conditions as installations were compelled to use the techniques specified by the SFI rules.

However, production strategies under the SCL scenarios were sensitive to changes in bird price. When the price received for broilers rises above the baseline, it becomes more feasible to maintain production at the units in closest proximity to the nature reserve, by using the tiered floor system. When prices fall below those in the baseline, the solution makes more limited use of the tiered floor system, as it is less viable, and reduces production levels in the units closest to the nature reserve, using this extra slack in NH_3-N emissions to produce birds on a PIMS elsewhere.

The price received for manure with dry matter content below 60% was found to be critical to the optimal solution. If this value remained at or above the baseline value, then the tiered floor system remained a viable abatement option. However, when this value was reduced it became more profitable to decrease production than to use the tiered-floor system. This is because the manure sales generate the majority of the revenue gained from this system and so the price is crucial for its viability.

5 Conclusions

This paper investigated two potential responses to the impacts of NH_3 emissions from a case study poultry installation and deposition at a nearby SSSI. The first response was the IPPC Directive delivered through SFI rules. This was interpreted in more extreme form than might be applied in practice as requiring adoption of a PIMS. The use of this system is capable of making reductions in NH_3-N emissions relative to those arising from phased feeding. These reductions are effectively costless since the savings in feed and increase in broiler meat quality covers the cost of implementing the system (Filmer, 2003). However, such reductions would not be effective in reducing N deposition at the nature reserve to within the critical load. Thus, although the PIMS system could achieve reductions in NH_3 emissions, it was clear that further reductions are required to achieve critical loads of N deposition at the nature reserve. Thus more needs to be done in order to achieve adequate environmental safeguards.

The concept of Significant Contribution Limits (SCLs) was introduced to define restrictions required on the emission of N from the installation in order to meet the critical load at the nature reserve. Achieving SCL constraints at baseline prices entailed the reduction of bird numbers at the units closest to the nature reserve, which were the largest contributors of N deposition to the nature reserve. This highlighted that the distance between the source and receptor is a critical factor in N deposition. If the poultry installation could be sufficiently distanced from the nature reserve, the impacts of N deposition from the installation would be reduced.

This has important implications for the future location of intensive livestock units. Regulations could be set to ensure that new livestock units are sufficiently distanced from sensitive areas lessening the need for N abatement, which has proved to be expensive in the LP models. However, decisions would have to be made at the point at which the location of a unit was first established. This could provide a means of achieving critical loads on sensitive areas, without significant reductions in net margins on farms. It must be noted though that although the sensitive areas would be protected, such a strategy would not reduce the total amount of NH_3-N being emitted or other associated environmental impacts.

The LP model included a range of abatement techniques, as listed by the EU BREF document (EC 2001) that could be used as BAT to reduce N emissions from the installation. The tiered floor system was found to be an effective system for reducing NH_3-N emissions from the installation, this achieved a positive net income when the price of birds (which fluctuates markedly) remained at or above the baseline level. However, it is not necessarily viable at lower prices. Furthermore, the profitability of this technique is also dependent on the price received for the manure sold to the power station or for application to agricultural fields. Using this system would imply that the broiler installation would primarily be producing manure for its calorific and fertiliser value, which generates a larger proportion of net income, than is gained from the production of meat.

The perforated floor system was not selected in any of the LP solutions as the tiered floor system could achieve greater NH_3-N emission reductions at lower cost. The EU BREF document also listed chemical wet scrubbers as a potential abatement technique, but again, the model did not select it in any scenario as it was outperformed by the tiered floor system and was a more expensive abatement technique than reducing production.

Given these limitations in the range of abatement techniques available, any legislation aiming to achieve critical loads could only be achieved at a significant cost to the poultry industry. Such legislation could potentially leave installations that are in close proximity to sensitive areas no option other than to decrease production.

It is worth noting of course that the results presented here are specific to the case-study installation. Therefore, they may not be applicable to all situations in the poultry industry. Furthermore, NH_3 has several impacts in the environment; this paper used N emission and deposition at a nearby nature reserve as an indicator of the effectiveness of policy responses. Thus, further work is needed in order to generalise the results and evaluate the wider environmental issues.

6 The way forward

At present, the national-scale policies mean that all farmers could be required to take action in the same way regardless of their particular circumstances. Yet for some farmers such imposition of regulation might be less warranted because there is no vulnerable site nearby. Other farms, in close proximity to a vulnerable site, may be causing substantial local impacts and the implementation of the national 'standard farming guidelines' would not be sufficient to protect that site. Thus while existing policies obviously have benefit for reducing total national emissions, their limitations point strongly to the need to consider the landscape-scale land use planning as a means to reduce impacts. It is also apparent that the economics of broiler production are substantially determined by the local availability of revenue generating outlets for the manure, such as a power station or agricultural fields.

This paper demonstrated that as the distance between the source and receptor increased, N deposition decreased. Therefore, the land use planning system could provide an instrument to determine whether or not a poultry installation and associated activities should be sited in certain locations. Here the EA and other statutory bodies could be given powers to object to planning applications on the grounds of local environmental sensitivity. It should be noted that currently certain agricultural activities are not considered development for planning purposes. However, it has recently been established that where planning permission is required for associated building development, if that development or any of the associated agricultural activities were to have an impact on a special area of conservation, the whole development may be refused according to provisions embodied under the Habitats Directive (Sutton, 2004). Thus, this may be a possible cost-effective alternative for reducing N deposition on sensitive receptors.

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