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SID 5 Research Project Final Report

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Project identification

1. Defra Project code: NT2511
2. Project title: Cost Curve of nitrate mitigation options
3. Contractor organisation(s):
   Institute of Grassland and Environmental Research
   North Wyke, Okehampton, Devon
   EX20 2SB
4. Total Defra project costs: £ 95,485
5. Project: start date .... 01 April 2003

   end date .... 01 July 2004

6. It is Defra's intention to publish this form.
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   Defra recognises that in a small minority of cases there may be information, such as intellectual property or commercially confidential data, used in or generated by the research project, which should not be disclosed. In these cases, such information should be detailed in a separate annex (not to be published) so that the SID 5 can be placed in the public domain. Where it is impossible to complete the Final Report without including references to any sensitive or confidential data, the information should be included and section (b) completed. NB: only in exceptional circumstances will Defra expect contractors to give a "No" answer.
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   (b) If you have answered NO, please explain why the Final report should not be released into public domain

Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

Tackling diffuse pollution of water bodies from agriculture is a top priority specifically in relation to the implementation of the Nitrate Directive but also in preparation for management of river basins for eventual compliance with the Water Framework Directive. This requires the identification of a set of measures for nitrate mitigation on farms, assessment of the likely effectiveness and ease of implementation of each measure and calculation of their costs to the farmer. This project aimed to obtain the relevant information for fulfilling these requirements and to produce nitrate cost-curves as a means of expressing the cost-effectiveness of measures for implementation in both arable and livestock systems.

First a comprehensive review of the literature was conducted and from this, information was extracted to assemble a matrix of measures each for arable and livestock agriculture. The appropriateness and relative importance of the initial list of measures identified as potentially useful were deliberated upon at a Health Check meeting involving a range of stakeholders and consolidated matrices were agreed. Measures could be grouped according to whether they involved manipulating the management of fertiliser, the crop, the animal, manure or soil.

Farming system typologies were defined, based on expert opinion and representing the main arable and grassland systems to enable the impacts of implementing each measure to be modelled and costed. These typologies were as follows

Arable: A series of 6-year crop rotations were defined on sandy and clay soils, each with and without manure applications. Additionally, pig rearing was included within the sandy soil rotation. These rotations were envisaged to operate in eastern counties of England.

Grassland: Three baseline systems were defined as 1. Intensive dairy farming in 3 locations (West Wales, Devon and South Cheshire). 2. Suckler beef rearing in 2 locations (Cumbria and County Durham). 3. Upland sheep in 2 locations (Cumbria and County Durham). Each location had a typical soil type associated with it.

Nitrate leaching from each of the baseline systems was then calculated using appropriate N cycling models:- NITCAT and MAGPIE for arable and NGAUGE/NCYCLE for grassland. The same models were then used to simulate the impacts of those measures from the consolidated matrices judged to be the most effective and practicable.

The cost of implementation of each measure was calculated using expert farm economics knowledge and available data sources. The cost-effectiveness of each measure was calculated and expressed as £ per kg N leaching reduced per year. For arable systems this was averaged over the course of the whole rotation. These results were expressed as bar charts and with conventional cost-curves. Cost-curves can be misleading as they suggest that effects of measures are independent and that reductions in nitrate leaching are additive, neither of which may be the case.

With the arable systems there were complex effects of measures on nitrate leaching due to interactions of crop sequences in the different rotations, manure management, presence or absence of pigs and soil conditions. Although there was limited scope for decreasing nitrate leaching from sandland rotations, the most effective measures on arable systems generally were those involving manure management (both timing and accounting for N content) and the introduction of grass set-aside. Leaching reductions with these ranged between 12-50% and between 43->90%, respectively. However, both of these categories of measure incurred relatively high costs of implementation. The least costly, most easily implemented sets of measures were those involving fertiliser management and the use of cover crops. While, some of these were calculated to be either cost neutral or providing small benefits on implementation, reductions in leaching were generally modest and ranged between 1-15%. Cost-effectiveness of the full set of measures modelled ranged between slight negative costs (benefits) per kg N reduced per ha for cover crop and fertiliser management measures to typically £3 and £10 per kg N reduced per ha per year for manure manipulation and use of grass set-aside respectively.

With the grassland systems, the modelling shows there to be a more direct link between N inputs, production levels and N losses compared with arable systems. Therefore, any measure that reduced animal production such as reduced fertiliser input, stocking rate and grazing time was generally effective but costly. On dairy farms the most effective measures were those involving reductions in intensity of management, either due to reductions in fertiliser inputs or stocking rate or grazing time. Reductions in leaching due to these ranged between 2.9 and 14.6 kg N ha^{-1} (9-33%), with costs ranging between 92.6 and 207.3 £ ha^{-1}, and cost effectiveness ranging between 6.3 and 37.3 £ per kg N per ha reduced per year. The least costly options involved adjustments to fertiliser to take account of N in manures, N from mineralisation and the balance with other nutrients. The cost effectiveness of direct manure management measures ranged between 13.5 and 26.4 £ per kg N per ha reduced per year, these relatively effective measures also being costly to implement due to increased storage and transport costs. There were quite large differences between the cost effectiveness of measures applied in different locations with steepness in cost curve in the order South Cheshire<West Wales< Devon. This effect is mainly due to changing soil conditions rather than location *per se*, with the effectiveness of measures on freer draining soils being greater, but having similar cost of implementation.

The relative cost-effectiveness of the different nitrate mitigation measures implemented on beef and sheep farms was calculated to be similar to that with dairy above, but levels of nitrate leaching per ha from beef and sheep farms were in general smaller than from dairy.

As with the arable systems, some of these measures were calculated to be ‘win-win’ solutions, as small benefits, not costs would be accrued by the farmer. Manipulation of feed quality to improve rumen capture of N was not generally effective in reducing nitrate leaching. This was mainly due to an assumption made in the model simulations, which was that a farmer implementing such a measure would do so to <u>increase</u> production at the same level of inputs, rather than decrease inputs (e. g. fertiliser) while achieving the initial baseline level of production. The distinction between these motives and consequent implementation action is very important when considering the value of any measure for nitrate mitigation.

The results of this study show that generally, measures to mitigate nitrate appear to be more costly to implement on grassland, due to the greater value of the product per ha coupled with the more direct interrelationships between N inputs, outputs and losses within grassland systems. With arable systems there is greater scope for implementation of low-cost measures of low-moderate effectiveness. However, costs of highly effective, high-cost measures in either sector may need to be spread over larger land use units than the single farm (e. g. catchments) in order to facilitate their economic implementation. Further research is required to evaluate potential for nitrate mitigation at broader scales, to identify the best ways of implementing the most cost-effective measures and to quantify impacts of implementation on losses of other pollutants to water and the atmosphere (pollution swapping).

Project Report to Defra

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:
   - the scientific objectives as set out in the contract;
   - the extent to which the objectives set out in the contract have been met;
   - details of methods used and the results obtained, including statistical analysis (if appropriate);
   - a discussion of the results and their reliability;
   - the main implications of the findings;

- possible future work; and
- any action resulting from the research (e.g. IP, Knowledge Transfer).

1. BACKGROUND

Improvement of water quality, and particularly agriculture's role in this, has become a priority issue. The EC Nitrate Directive and associated legislation limits nitrate concentration in surface and groundwaters to 50 mg l^{-1}. The UK Government has responded to the requirements of this Directive by delineating Nitrate Vulnerable Zones (NVZ) to cover 55% of England. Implementation of agricultural management rules required to comply with the Directive within NVZs is expected to have significant consequences for water quality and the economics of the various sectors of agricultural land management. Furthermore, NVZ Action Programmes are reviewed and revised on a 4 yearly cycle. The Water Framework Directive (WFD, ratified December 2000) and the daughter Groundwater Directive require the quality of all waterbodies to be assessed and actions set in place to improve quality where necessary. The Directives, of course, cover all aspects of water quality (ecological and chemical) and water quantity, and all influences on these (rural and urban). Nevertheless, agriculture will play a dominant role in many catchments. Coincidental with this, Defra has identified diffuse pollution from agriculture as a priority issue.

As much as 70% of nitrate in water is thought to derive from agriculture [1]. Much is already known about nitrate loss from agriculture. Several reviews go some way to summarising the current state of knowledge [e.g. 1, 2, 3, 4 and 5]. Factors that encourage nitrate loss include:

- Over-fertilisation of crops
- Significant periods of bare soil during the winter drainage period
- Excessive numbers of livestock and consequential overloading with manure
- Inappropriate use of manures, including not accounting for N content when deciding fertiliser policy for the following crop

Mitigation methods can be developed to address these causes [3], but issues of practicality and cost-effectiveness have to be recognised if successful, cost-effective 'Programmes of Measures' (PoMs) are to be drawn up (a requirement of the WFD). The EA started to make such an assessment [1], and there are a number of projects currently working on a methodology for the economic assessment of programmes of measures across all sectors (including agriculture).
To support these developments, work needs to be undertaken to make an assessment of:

- cost-effectiveness for nitrate mitigation
- acceptability to the industry
- practicality
- time-scale of effectiveness
- interactions with other forms of pollution (important because all forms of diffuse pollution need to be reduced)

The purpose of this project was therefore to identify and categorise potential strategies for reducing nitrate pollution from agriculture and to assess their cost, their effectiveness and ease of uptake.

2. METHODOLOGY

2.1 Review

A major (90 page) review of the effectiveness of measures to reduce nitrate leaching from UK agriculture is attached as Appendix 1. This deals with the effectiveness of measures within arable and grassland sectors separately and under each sector divides the measures according to whether they are based on plant, soil, fertiliser, animal or manure managements. From the information provided by the review, a matrix defining the combinations of measures and land-use systems (arable or grassland) to be modelled and assessed for cost-effectiveness was drawn up through expert opinions and interpretations made by the project team. This was presented at the project 'Health Check' to a group representing Defra and the EA, and updated in response to comments made by the group. The finalised matrices for arable and grassland sectors are respectively attached in Appendices 2 and 3. Definitions of the systems used for implementation of the measures were arrived at again using expert opinions gathered by the project team. Systems were defined in relation to agro-climatic typologies. A total of 262 system/measure combinations (80 arable and 182 grassland) were thus defined for modelling and costing, resulting in 250 runs for the arable and 1000 runs for the grassland model being made.

2.2 Derivation of cost curves for arable systems

The aim of this phase of the project was to develop 'typical' rotations against which to test and compare measures for decreasing nitrate loss. The setting of these typical rotations and the definition of management practices within the rotations (i.e. the baseline conditions) were critical, because the success of management practices has to be judged against this baseline. Soil-type and climate typically determine rotations. Therefore, generally, arable crops predominate in the drier east, and rotations that include root crops predominate on lighter textured soils. However, management within rotations is less easy to categorise as 'standard practice', because farming statistics show there is considerable variation between farms (perhaps, not surprising as individual businesses respond differently to the market). As examples, we can consider two management practices that impact on nitrate leaching:

- Fertiliser amount
- Timing of manure application

Fertiliser amount

The shape of the nitrogen response curve (Fig. 2.1) shows that post-harvest nitrate leaching increases disproportionately once the crop's optimum requirement has been reached. Thus, the fertiliser rate at which we set our standard management practice will affect the baseline quantity of nitrate loss and the size of the benefits achieved from applying measures that decrease fertiliser inputs.

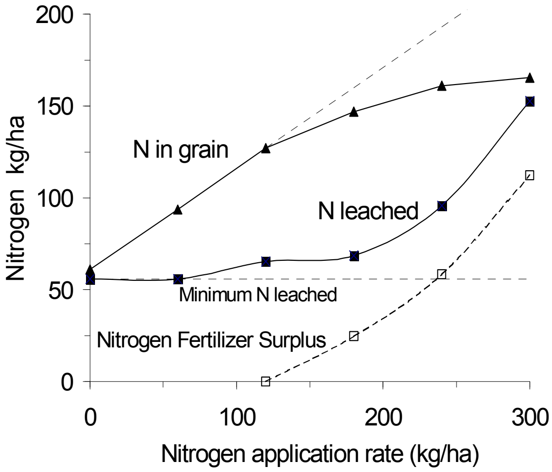

Figure 2.1. Relationship between fertiliser inputs to a cereal crop, N offtake in grain, and nitrate leaching.

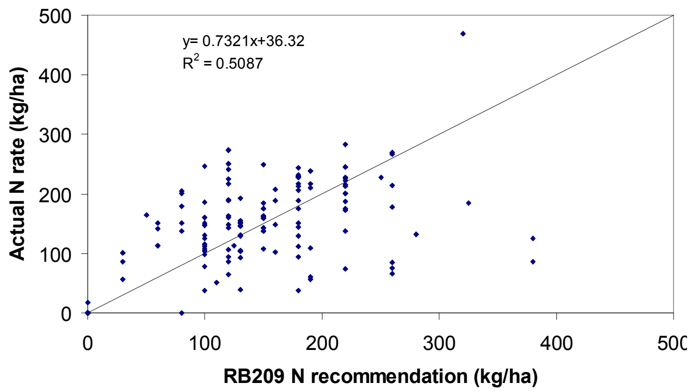

Figure 2.2. Relationship between recommended (RB209) and actual N fertiliser rates for crops following cereal crops. 1:1 line shown.

The British Survey of Fertiliser Practice (BSFP,[6]) provides information on the average amount of fertiliser applied to each crop. Table 2.1 shows the average application for a number of crops and the recommended amount of N according to Defra's fertiliser recommendation book 'RB209' [7]. The average is close to, or below, the recommended amount for most crops. However, the BSFP also shows that some crops appear to be significantly over-fertilised (e.g. Fig. 2.2) and it is in these situations where we need to focus improved measures. Nevertheless, what do we consider as baseline fertiliser levels? The BSFP also provides information on manure timings and shows that, for all of the materials surveyed, a significant proportion is spread in each season. Thus, it is difficult to define a 'standard' application time.
It was, therefore, necessary to develop typical rotations and management practices for testing mitigation methods. The rationale for choice of these rotations/practices is described below.

Description of rotations

Given the variations in farm management practices, the design for rotations and baseline practices was based on expert judgement. The aim was to define 'typical' practices that did not reflect extremes but, also, did not completely follow Codes of Good Practice. Thus, rotations:

- were based on sandy and clay soils to reflect differences in leaching risk;
- had cropping that reflected differences in management on the contrasting textures;
- were run with and without manure inputs, again to provide differences in leaching risk.

Table 2.1. Total Fertiliser use Great Britain 2002 (source: BSFP, arable only).

	Overall application rate ($kg\ ha^{-1}$)	RB209 estimated rate ($kg\ ha^{-1}$)	Fields in sample
Winter Wheat	193	220	2363
Spring Barley	110	130	747
Winter Barley	154	180	751
2nd Early/Maincrop potatoes	158	160[1]	167
Sugar Beet	106	100	225
Winter oilseed rape	207	220[2]	47
Forage maize	47	80	130
Peas – human consumption	6	0	30

Peas – animal consumption	6	0	47
Beans - animal consumption	4	0	29
Vegetables (brassicae)	247	300[3]	166
Vegetables (other)	59	60[4]	66

[1]midrange for Group 3 grown for 90-120 days; [2] includes seedbed N, [3] sprouts; [4]carrots

The (non-manure) rotations were based on current cropping at two ADAS Research Centres – Gleadthorpe (sand) and Boxworth (clay), though inputs were chosen as described above. Manure inputs included a mix of manure types and application times (again, reflecting differences in leaching risk). The source of manure to these arable rotations was assumed either to be imported or supplied from an on-farm enterprise. Import or enterprise costs were not factored into the calculations. Fertiliser inputs were not initially adjusted to take account of manure applications. The BSFP suggests that the allowance, on average is minimal (Table 2.1) and we felt, therefore, that this was an unnecessary refinement. A fifth rotation combination was included, whereby outdoor pigs were included in the sandland rotation. Tables 2.2 and 2.3 summarise the rotations for sand and clay soils, respectively. Additionally, nitrate leaching models (see later) were run to simulate dry (east) and wet (west) climates.

Choice of measures

An exhaustive list of measures that could be adopted to decrease nitrate leaching was compiled and reviewed as a part of the overall project (see CSG15 report and accompanying Appendix 2). The measures were categorised as follows:

- Soil-based, e.g. cultivation management.
- Plant-based, e.g. change rotation or manage crops to use nutrients as efficiently as possible.
- Animal-based, e.g. manage diet to reduce nutrient output in manure.
- Manure management, e.g. timing, application method or rate.
- Fertiliser management, e.g. timing or rate.
- 'Other' or combination of measures, e.g. NVZ measures.
- Climate-based, e.g. irrigate crops on droughty soils.

The full list of about 50 measures was assessed in terms of ease of applicability, efficacy, time scale of effectiveness, etc to produce the matrix of measures. The Project Steering Group then produced a short-list of measures that were analysed in more detail (Appendix 2). In fact, not all of these measures were applicable to the rotations we had modelled and so not all could be investigated in detail.

Assumptions in calculating the effectiveness of measures

Effects on yields/quality

Variations in yields and N optima are large between farms and between fields within farms, as are the shapes of the N response curves. Consequently, any calculated yield penalties/advantages with reduced/increased N fertiliser inputs differ with individual circumstances. The generalised economic calculations in this project were based on 'average' response curves calculated from a number of individual fertiliser experiments [8], ranging from 25 experiments for potatoes to 92 experiments for winter barley. These average data provided calculated N optima ('Nopt' kg ha^{-1} and associated yields). The data provided in the paper allowed us to back calculate the shape of the average response curve and fit a linear plus exponential curve to describe the change in yield with applied N [9]. The linear plus exponential functions were then used to calculate changes in yield from our baseline assumptions in Tables 2.2 and 2.3. Throughout our calculations, it was assumed that the published recommended rate (RB209) was the optimum fertiliser rate. Thus, because we described baseline yields and fertiliser rates in Tables 2.2 and 2.3, it was necessary to calculate the yield associated with Nopt (Appendix 2).
The shapes of these average response curves were such that N applications well above the optimum did not severely decrease yield. In practice, in individual fields, large yield penalties have been noted in cereals when excess N has caused lodging. It was also assumed that all cereal crops were fertilised for yield only, not quality. Therefore, changes in quality from changed fertiliser policy were not taken into account.

Table 2.2. Sandy soil rotation

(a) Without manure

	Crop	Sown	Harvest Date	N fert kg ha^{-1}	Yield t ha^{-1}	Harvest residue	Irrig?	RB209 kg N ha^{-1}
Year 1	Potatoes	1-Apr	15-Oct	250	45	Ploughed in	yes	230
Year 2	S Wheat	15-Jan	1-Aug	180	7	Ploughed in	no	160
Year 3	W Barley	15-Sep	15-Jul	170	6.5	Baled	no	160
Year 4	S Beet	1-Apr	15-Dec	130	40	Ploughed in	yes	120
Year 5	S Barley	1-Mar	20-Jul	80	6	Baled	no	90
Year 6	W wheat	15-Oct	30-Jul	170	7	Ploughed in	no	160

(b) With manure

	Crop	Sown	Harvest	Nfert	Yield	Harvest	Irrig?	Manure		
			Date	kg ha^{-1}	t ha^{-1}	residue		type	t ha^{-1}	time
Year 1	Potatoes	1-Apr	15-Oct	250	45	Ploughed in	yes	Cattle FYM	50	Jan
Year 2	S Wheat	15-Jan	1-Aug	180	7	Ploughed in	no			
Year 3	W Barley	15-Sep	15-Jul	170	6.5	Baled	no			
Year 4	S Beet	1-Apr	15-Dec	130	40	Ploughed in	yes	Broiler litter	10	Sept
Year 5	S Barley	1-Mar	20-Jul	80	6	Baled	no	Pig FYM	50	Jan
Year 6	W wheat	38275	30-Jul	170	7	Ploughed in	no	Pig slurry	40	Sept

(c) With pigs

	Crop	Sown	Harvest	N fert	Yield	Harvest	Irrig?
			Date	kg ha^{-1}	t ha^{-1}	residue	
Year 1	Potatoes	1-Apr	15-Oct	225	45	Ploughed in	yes
Year 2	S Wheat	15-Jan	1-Aug	180	7	Ploughed in	no
Year 3	PIGS	grass		0	-	-	no
Year 4	PIGS	grass		0	-	Ploughed	no
Year 5	WOSR	15-Aug	15-Jul	200	3.5		no
Year 6	W wheat	15-Oct	30-Jul	140	7	Ploughed in	no

Table 2.3. Clay soil rotation

(a) Without manure

	Crop	Sown	Harvest	N fert	Yield	Harvest	RB209
			date	kg ha^{-1}	t ha^{-1}	residue	kg N ha^{-1}
Year 1	O rape	15-Aug	15-Jul	210	4	Ploughed in	220
Year 2	W Wheat	15-Oct	20-Aug	160	9	Ploughed in	150
Year 3	W Beans	30-Oct	10-Sep	0	4	Ploughed in	0
Year 4	W Wheat	15-Oct	20-Aug	200	9	Ploughed in	180
Year 5	W Barley	25-Sep	30-Jul	160	8	Baled	180

(b) With manure

	Crop	Sown	Harvest	N fert	Yield	Harvest	Manure		
			Date	kg ha^{-1}	t ha^{-1}	residue	type	t ha^{-1}	time[1]
Year 1	O rape	15-Aug	15-Jul	210	4	Ploughed in			
Year 2	W Wheat	15-Oct	20-Aug	160	9	Ploughed in	pig slurry	40	10-Oct
Year 3	W Beans	30-Oct	10-Sep	0	4	Ploughed in			
Year 4	W Wheat	15-Oct	20-Aug	200	9	Ploughed in	pig slurry	40	10-Oct
Year 5	W Barley	25-Sep	30-Jul	160	8	Baled			

[1]Manure incorporated immediately

<u>Effects on fertiliser and manure inputs</u>

Baseline fertiliser inputs were based on expert opinion. Fertiliser rates for other measures were adjusted thus:

- Fertiliser rates for measure Fa1 ('use of a reliable recommendation system') were calculated from the industry standard (RB209).
- Measure Fa2 used a standard 20% reduction below baseline application rates, which equated, on average, to about 15% below the optimum fertiliser rate. Measure Fa5 took account of the N supply from manure, based on the principles in MANNER [10], i.e. N supply is affected by type of manure, rate and time of application, soil-type and subsequent rainfall as well as method of incorporation. A further refinement of the modelling was that the residual effect of manure application was also taken into account, not just the effects on N supply in the year of application).
- Switching manure applications from autumn to spring saves N from leaching (measures M1 and M2). There is additional benefit when the 'saved' N is taken into account by reducing the subsequent N fertiliser recommendation.

Nitrate modelling

Field-scale models were used to estimate the impact of farming practice, site and weather on nitrate loss to water. The following were used: the NITCAT model [11], which contains embedded within it the MANNER model [10] of the fate of N from manures, and which uses the IRRIGUIDE model [12] to estimate water flux. This model suite has been developed on the basis of Defra-funded experimental results, and is specifically designed to be responsive to those changes in manure and fertiliser management required or likely within NVZs. The model system has been used over a number of years to assess impacts within NSAs [13].

2.3 Derivation of nitrate cost curves for grassland systems

In this section we select and describe representative grassland systems in the UK where nitrate leaching was estimated and nitrate mitigation options applied. The cost of the application of these measures was also estimated in order to construct a cost curve.

Description of systems

The systems were established as representative of dairy, beef and sheep farms. We initially listed 7 grassland systems representing livestock management practice in the UK [14]. These were considered baseline systems and included dairy of high, medium and low intensity; beef mixed with sheep; suckler beef; sheep mixed with dairy; upland sheep as well as a dairy complying with NVZ regulations. The systems were located in lowland areas such as West Wales, South West England, North West and North Midlands, the Cotswolds, Hampshire and East Anglia. The upland areas were in Cumbria and Durham. From this list only 3 systems were chosen to be evaluated in the cost curve analysis (Appendix 3 includes the management for the three systems):
1. Dairy farming. Intensive, with inorganic fertiliser applied at 250 kg inorganic N ha^{-1}. Slurry was applied at 40% Feb-Apr, 10% May-July, 24% Aug-Oct and 26% Nov-Jan. Silage fields also received inorganic N (depending on the number of cuts, up to 346 kg N ha^{-1}) + slurry N. Silage was followed by aftermath grazing. This system was located in three areas: West Wales, Devon, South Cheshire.
2. Suckler beef. Fertiliser N rates were 100 kg N ha^{-1} on silage ground, and 60 kg N ha^{-1} (plus manure) on grazed fields Stocking rate was 0.8 cows ha^{-1} and 0.7 calves ha^{-1}. Feed was 280 kg concentrate cow^{-1}. Locations: Cumbria, County Durham.
3. Upland sheep. Swards were: grass receiving 80 kg N ha^{-1} on grazed only swards, and 120 kg N ha^{-1}. Stocking rate 8 ewes ha^{-1} and 1.4 lambs ewe^{-1}. Concentrate feeding was at 100 kg ewe^{-1} yr^{-1}. Locations: Cumbria, County Durham.
Every location had a soil type associated:
-Devon and West Wales had a clay loam texture and poor drainage.
-South Cheshire, Cumbria and Co. Durham had a loam texture and moderate drainage.
The climate was (temperature, C; rainfall, mm; deposition, kg N ha^{-1} y^{-1}):

Devon:	11-11.5; >500; 25
West Wales:	11.5-12; 350-400; 15
South Cheshire:	11.5-12; 300-350, 25
Cumbria:	<9, >500, 35
CoDurham:	9-10, 350-400, 35

Choice of measures

The full list of measures proposed for the grassland systems is shown in Appendix 3. They were classed as:
- Soil-based, e.g. avoid drainage of grassland sites.
- Plant-based, e.g. sow modern grass varieties.
- Animal-based, e.g. adopt zero grazing.
- Manure based, e.g. apply manures uniformily.
- Fertiliser based, e.g. apply ammonium-based fertiliser in spring.
- ‘Other’ or combination of measures, e.g NVZ measures.
- Climate-based, e.g. irrigate grassland to remedy water deficits.

The measures were scored as described in the arable section and a total of 25 measures were selected to work on (see Appendix 3). From these a second scoring was carried out in order to select the most relevant measures for each grassland system and only the ones resulting as essentials (score 1) were modelled.

General assumptions in calculating the effectiveness of measures:

- all the manure produced during housing was applied to the farm.
- only NH_4NO_3 fertiliser was considered.
- only slurry was considered in the dairy and beef systems, and FYM in the sheep system.

The details of the fields comprising the farm and their management, inorganic fertiliser applications, concentrate feeds and organic fertiliser applications for the baseline systems are shown in Appendix 3.

Nitrogen modelling

The model used to calculate nitrate leaching from the grassland systems was NGAUGE [15]. Where NGAUGE could not cover the mitigation measure NFixCycle was used (simulation of N fixation by white clover sword).
The input requirements of the model were:

- Inorganic N applied per month, amount and type.
- Organic fertiliser applied, amount, type (slurry or FYM) and method of application (surface or injection).

- Age of grassland.
- History of grassland.
- Soil texture (classes: sandy, sandy loam, loam, clay loam, loam).
- Drainage (classes: freely, median, undrained).
- Grazing season
- Climate: rainfall (6 classes), temperature (5 classes), N deposition (3 classes).

As the original version of the NGAUGE model could not account for some of the changes required in order to evaluate some of the measures, some modifications were introduced (Agustin del Prado, pers. Comm.) The first modified version was able to include concentrate feeds in the input window. The second modified version allowed changes in the u factor (fraction of plant N taken by the animal or cutting), h factor (N uptake by the plant), and the animal factor that allows changes in the amount of N that goes into milk. Another version was needed to allow the evaluation of the effect of reseeding grassland in spring or autumm.

The assumptions made for each of the mitigation measures were:

Dairy system:

- **cultivate and reseed grassland in spring (G3)**. The baseline runs are characterised by fields of 4-6 and 11-20 years old. Reseeding in these conditions will not affect the results of the model as it only evaluates the effect in the first year. The measure was evaluated by estimating the effect of reseeding when all the grass is <2 years old and both, when reseeding is done in the autumn and spring.
- **select high sugar grasses for grazing and cutting (G6)**. It was decided to include this measure in the diet measures (Ac3-Ac6).
- **change to grass/clover swards and other forage legumes (G11)**. The model NFixCycle was used to calculate the losses. However, the baseline values obtained with NFixCycle did not agree with the results from NGAUGE, one reason being that NFixCycle does not consider concentrates for example. So the baseline and G11 measure were evaluated using NFixCycle and the percentage reduction in leaching was estimated by taking into account the fixed N. This percentage was used to estimate the leaching from the baseline NGAUGE run (see Appendix 3). The corresponding percentages of decrease for Devon, West Wales and South Cheshire were 20, 24 and 15.8%. This gives final leachate values when using grass/clover of 25, 27.6, 43 kg N ha^{-1} at the three sites if using the values given by NGAUGE.
- **replace grass silage with forage maize or fodder beet (G12)**. It was assumed that some of the silage was replaced by maize. Valk [16] obtained an increase in milk yield (10%) when introducing maize. Also Phipps et al. [17] obtained an increase of 14% milk yield. Metcalf et al [18] did not find a difference in milk N when using maize. Baez et al. [19], used maize + ryegrass as a cover crop and leaching was <20 kg N ha^{-1} (silty clay loam). From the Midas [20] report a system PRG/maize with 261 kg N ha^{-1} on grass and 82 kg N ha^{-1} on maize produced 5.4 t DM ha^{-1} (PRG) and 13.3 t DM ha^{-1} (maize) with a stocking rate of 1.89 LU ha^{-1}. The leaching was 27 kg N ha^{-1}. Jarvis et al. [21] used part of the farm for maize which received manure but no fertiliser. In the same study there was an increase in utilisation efficiency of dietary N of 1%. Maize dry matter contained 1.5% N. The third field of the farm in our study (1cut+grazing) was set up for maize. The losses for the farm were calculated (only 2 fields) assuming the slurry produced is applied in the whole farm (including the maize field). Maize silage was also added to the total silage produced by grass when running the model to calculate the excreta in the housing period and to calculate the slurry to apply. The third field (maize) only received slurry. It was then assumed an increase in milk production to 24% (it was 23% in baseline). Also the losses are assumed to be 25% of those under grass in the conventional management [21]. It was assumed that the losses from the maize field were the same for the three locations (clay loam and loam moderate soils).
- **reduce the rates of fertiliser N applied to grassland by 20% (Fg1)**. Only the fertiliser inputs were changed by decreasing the amount by 20% on each application.
- **avoid early spring, late autumn applications or during drought (Fg2)**. Set the last application of inorganic fertiliser (August) to zero. The new fertiliser rates are shown in Appendix 3.
- **adjust fertiliser rates to allow for N supplied in manures (Fg5)**. The NH_4^+-N (50% of total N, see Appendix 3) in slurry was subtracted from the inorganic N applied and this set new fertiliser rates. This doesn't consider the mineralization in slurry N. The new fertiliser rates were: 206 kg N ha^{-1} for field grazed only; 289 kg N ha^{-1} for field grazed+2 cuts and 248 kg N ha^{-1} for field grazed+ 1 cut.

Although manure was considered to be applied in the middle of the quarter (Appendix 3), for example in March in the first quarter, it was spread per month (see Appendix 3) in order to subtract from the inorganic fertiliser in each month. For example, the 23 kg N ha^{-1} in Feb-April was spread in two months, March and April when there is fertiliser application. As a result 11.8 kg N ha^{-1} are subtracted from the inorganic fertiliser rate for each of these two months, that is from 29 and 81 kg N ha^{-1}.

- **adjust fertiliser rates for soil N-min (tactical fertiliser strategy) (Fg6)**. According to Titchen and Scholefield [22] limiting N fertiliser additions to produce a mineral N profile that did not exceed an upper limit of 45 kg mineral N ha^{-1} improves the efficiency of N use and reduces leaching. The applications of inorganic N were decreased in April and July by 40% in order to evaluate the measure.
- **correct soil deficiencies of S and K, particularly in silage fields (Fg8)**. Correcting soil deficiencies in S and K is expected to improve the uptake of N by the plant (h factor in the model) especially in silage fields. The NGAUGE model was modified in order to increase the efficiency of N uptake by 10% .
- **reduce stocking rate by 20% (Ac1)**. As the stocking rate changes it affects the concentrate input per hectare in the farm. This is due to the fact that the concentrates distribution is calculated based on per head of livestock, with 80% supplied in the

winter (during housing) and 20% in the summer (grazing months). It was estimated how much fertiliser was needed to produce 20% less herbage. The model was run for 2 fertiliser rates additional to baseline, in order to calculate the N in plant product. The figure 'changes in silage N with fertiliser input' in Appendix 3 shows the results for the original fertiliser rates, 20% less fertiliser and 30% less fertiliser. Interpolating from here to get 20% less N in plant product (85.6 kg N ha^{-1}) a new fertiliser rate is required of 158.9 kg N ha^{-1} which means a reduction of 55% in fertiliser.
- **reduce length of the grazing day (daytime only) (Ac9)**. A way to deal with this measure is to shorten the grazing season. It was considered the same as Ac10.
- **reduce length of the grazing season (end in August) (Ac10)**. Reducing the length of the grazing season caused a change in the distribution of the concentrates (amount per month) as for this measure the amount given in winter and summer is the same (housing/grazing 6/6 months).
- **adopt zero grazing (Ac11)**. Zero grazing implies feeding of concentrates indoors all year. Also all the silage must be cut to be fed indoors. The amount of manure produced is larger than baseline and it was assumed that all was spread in the fields.
- **reduce the N surplus in the diet (reduce CP from 18 to 14%) (Ac2)**. This measure changes the amount of N provided by the concentrates. The model contains several options within the cake type that was used for the baseline runs. It was calculated that for a crude protein content of 14% the concentrate would have an N content of 2.48%. The closest compounds in the list within NGAUGE were wheat bran and rice bran with 2.4 %.
- **supply energy supplements to increase N recovery in rumen, feed supplements containing rumen-protected methionine/lysine, use total-mixed rations to allow more accurate diet formulations, use milk urea concentrations as indicator of N use efficiency (Ac3-Ac6), select high sugar grasses for grazing and cutting (G6)**. Based on the literature, the effect of diet on N utilisation produced an improvement of 10% (Cammell et al., 1999 in [23] page 17).
- **change to fewer, higher yielding cows (Ac7)**. This measure implies reducing the stocking rate but increasing the milk produced per LU. We reduced the stocking rate to produce the same amount of milk in total with 20% less cows. This implies that they should now produce 8750 l y^{-1}. The amount of grass fed in the baseline system per animal was 15 kg DM d^{-1}. With the new stocking rate the same amount of grass result in a rate of 19 kg DM d^{-1} (for 132 LU). According to Owen [24] the daily DM intake for a low yielder is 15.1 kg DM d^{-1} and a high yielder 18.9 kg DM d^{-1}. This increase agrees with our high yielding cows being fed the same total of grass as our baseline ones. Based on this the same amount of fertiliser and concentrates was given (as concentrates are per litre of milk produced and the total milk is the same, the total concentrates fed are the same). In consequence leaching will be the same as baseline.
- **avoid autumn applications - slurry, poultry manure, liquid digested sludge (M1)**. The autumn application of slurry was removed, and leaching was estimated (measure M1). This would imply transporting manure to other farms. In a different model run, the total slurry was distributed between the three applications left in the year, with 50% of the autumn application allocated to the spring application; 30% to the summer application and 20% to the winter application (measure M1a). This produced slurry application rates that were below 30 tonnes ha^{-1} (rates should be lower than 50 tonnes ha^{-1}, see Appendix 1).
- **restrict manure applications to safe time windows (M2)**. This was partly dealt with in measure M1. According to review soil should not be waterlogged, flooded, frozen hard or covered with snow. Difficult to simulate due to model restrictions.
- **apply manure at optimum rate (M3)**. This measure was dropped as it is not easy to evaluate due to model restrictions.
- **apply manures uniformly (M4)**. This measure was dropped as it is not easy to evaluate due to model restrictions.
- **transport manure to other farms (M8)**. The idea behind M1 (avoid autumn applications) was to eliminate the autumn application of slurry and this would then be transported to a beef farm. However, we have placed our beef systems in regions far away from the dairy systems making it difficult to justify transporting it. However, it was partially evaluated as measure M1a (see above).
- **combined NVZ restrictions (Z).** These rules state that organic manures in the whole farm including grazing deposition should not exceed 170 kg N ha^{-1} (total N). The model can not achieve the lower amounts of slurry as it is set up. Based on the NVZ guidelines report the amount of slurry expected from a 650 kg cow is 116 kg N ha^{-1}. This means that in our farm a total of 255 kg N ha^{-1} is theoretically produced (for 165 cows). In order to produce 170 kg N ha^{-1} we require a total of 110 cows, so a reduction of stocking rate of 33%. Concentrates were reduced accordingly and so was fertiliser applied.

Beef system

- **cultivate and reseed grassland in spring (G3)**. The baseline runs are characterised by fields of 4-6 and 11-20 years old. Reseeding in these conditions will not affect the results of the model as it only evaluates the effect in the first year. The measure was evaluated by estimating the effect of reseeding when all the grass is <2 years old and when reseeding is done in the autumn or spring.
- **select high sugar grasses for grazing and cutting (G6)**. The effect of improved diet was an increase in N utilisation of 10%.
- **change to grass/clover swards and other forage legumes (G11).** This was carried out as described in the dairy system. The result of the model runs showed that no fertiliser should be applied in this system when having a mixture of grass and clover.
- **adjust fertiliser rates to allow for N supplied in manures (Fg5)**. Subtracted the NH_4^+-N (50% of total N) in slurry from inorganic N applied and this set new fertiliser rates. It doesn't consider the mineralization in slurry N. New fertiliser rates are: 51 kg N ha^{-1} for field grazed only and 90 kg N ha^{-1} for field grazed+2 cuts. See example for Cumbria (Appendix 3).
- **adjust fertiliser rates for soil N-min (tactical fertiliser strategy) (Fg6).** According to Titchen and Scholefield [22] limiting N fertiliser additions produced a mineral N profile that did not exceed an upper limit of 45 kg mineral N ha^{-1}. The conventional treatment produced values of up to 75 kg mineral N ha^{-1} implying a 40 % reduction when controlling the fertiliser applied. The output mineral N in NGAUGE includes several forms of inorganic N including N in fertiliser,

mineralised N, urine N, input N from the atmosphere and carried over leachable N not leached in previous month. The applications of inorganic N in April and July were decreased by 20%.
- **correct soil deficiencies of S and K, particularly in silage fields (Fg8)**. Carried out as in dairy system.
- **reduce stocking rate by 20%** (**Ac1**). As the stocking rates change the concentrate input per hectare in the farm is changed. This is due to the fact that the concentrates distribution is calculated on a per head of livestock basis, with 80 % supplied in the winter (during housing) and 20 % in the summer (grazing months). The model was used to calculate the fertiliser rate required to produce 20 % less silage (at original, 80 and 60 % of the original fertiliser rate). The figure in appendix 3 shows the results for Cumbria where reducing fertiliser by 40% is enough to achieve the required silage.
- **reduce length of the grazing season (end in August) (Ac10)**. Reducing the length of the grazing season causes a change in the number of months winter/summer (6/6) which affects the distribution of the concentrates (amount per month). Grazing was ended in August instead of October.
- **avoid autumn applications - slurry, poultry manure, liquid digested sludge (M1)**. According to review (Appendix 1) greater losses are found when slurry is applied in the autumn compared with winter. Also the total slurry was distributed between the three applications left in the year, with 50% of the autumn application allocated to the spring application; 30% to the summer application and 20% to the winter application. This produced rates that were below 30 tonnes ha^{-1} (rates should be lower than 50 tonnes ha^{-1}, Appendix 1).

Upland sheep:

- **cultivate and reseed grassland in spring (G3)**. The baseline runs are characterised by fields of 4-6 and 11-20 years old. Reseeding in these conditions will not affect the results of the model as it only evaluates the effect in the first year. The measure was evaluated by estimating the effect of reseeding when all the grass is <2 years old and when reseeding is done in the autumn or spring.
- **select high sugar grasses for grazing and cutting (G6)**. The effect of improved diet was an increase in N utilisation of 10%.
- **correct soil deficiencies of S and K, particularly in silage fields (Fg8)**. Carried out as in dairy and beef systems.
- **reduce stocking rate by 20%** (**Ac1**). Similarly as the beef system, a reduction of 40% in fertiliser produced a reduction of 20% silage. The measure is then a combination of stocking rate reduction + 40% reduction in fertiliser.

3. RESULTS AND DISCUSSION

The results of the reduction in leaching derived from the models after the application of the mitigation measures for both, arable and grassland systems are presented in appendices 2 and 3 respectively (see Tables, both appendices). Bar graphs are also shown for all the systems studied (see figures 3.2 and 3.4 and appendices 2 and 3).
The financial benefits (£ ha^{-1}) were also included in the bar graphs (with costs having negative values), and both, leaching and financial penalty (per ha) were plotted as 'cost curves' [25]. Changes in outputs (milk, sheep and beef output; crop yields) and inputs (fertiliser, feed) resulting from the implementation of the nitrate mitigation measures on arable and grassland were specified by the expert team. The impacts of these changes on the net costs to the farm business were estimated using standard farm management data as given in [26] and [27]. In more complex situations (e.g. measures requiring changes in manure storage or transport) expert opinion was sought. All changes in inputs (seeds, fertiliser, feed), labour and capital inputs, stock, transport and machinery were included as relevant to the mitigation measure.
On some occasions there were savings as a result of changed practices. On others the mitigation measures imposed a net cost on the business. The assumptions made are summarised in appendices 2 and 3 (arable and grassland respectively). For arable, as with nitrate leaching losses, costs were averaged over the whole rotation (£ ha^{-1} yr^{-1}). For grassland, the costs were estimated for a year, and, in both arable and grassland per area unit (ha) and per unit N reduced (£ kg N $reduced^{-1}$ y^{-1}) (see Appendices 2 and 3).

3.1 Arable systems

Fertiliser inputs and yield effects

Details of the N inputs and calculated yields for individual crops within the rotations are given in Appendix 2. The averages for each rotation are shown in Table 3.1.

Table 3.1. Summary of fertiliser inputs (kg ha^{-1}) and calculated yields (t ha^{-1}), averaged over each rotation. Full details in Appendix 2. Includes only measures where fertiliser applications were affected.

Measure	Description	Clay		Sand		
		- manure	+ manure	- manure	+ manure	+ pigs
(a) Fertiliser inputs (kg ha^{-1})						
Baseline		**146**	**146**	**162**	**162**	**121**
Fa1	Improved fertiliser recs	140	128	152	123	110
Fa2	Reduce fertiliser by 20%	117	117	130	130	97

Fa5	Account for manure N	146	126	162	132	110
Fa5 Fa2	As above, then decrease 20%	117	101	130	105	88
M1 M5	Manure management 1	146	115	162	114	110
M2 M6	Manure management 2	146	115	162	110	121
(b) Yields (t ha^{-1})						
Baseline		**6.8**	**6.8**	**20.9**	**20.8**	**18.5**
Fa1	Improved fertiliser recs	6.8	6.8	20.9	20.9	18.4
Fa2	Reduce fertiliser by 20%	6.7	6.8	20.8	20.8	18.3
Fa5	Account for manure N	6.8	6.8	20.9	20.7	18.5
Fa5 Fa2	As above, then decrease 20%	6.7	6.7	20.8	20.9	18.2
M1 M5	Manure management 1	6.8	6.8	20.9	20.9	18.5
M2 M6	Manure management 2	6.8	6.8	20.9	20.9	18.5

For Measure P3 (cover crops), it was assumed that the cover crop had no effect on the yield of the following root crop (measure applicable only to sandy soils). In some rare situations, yield decreases following cover crops have been noted (e.g. effects on peas: [28]) but the effects can be minimised by management of the crop. In the case reported by Johnson et al. [28], the yield penalty was attributed to effects of drought on establishment of the following crop of peas in an exceptionally dry spring. Other series of experiments undertaken by ADAS have generally demonstrated no effect in the next crop. However, a second analysis was included in the economic assessment. Shepherd [29] reported a consistent yield benefit of cover crops (>10%) on the following potato and beet crops over a full 6 course rotation. The analysis was, therefore, repeated on the basis of this yield increase to potatoes and beet.

Measure Fa1 (use of a reliable recommendation system – in this case, RB209), resulted in an average reduction in N fertiliser inputs to crops on the clay soils (except beans) of c. 20 kg ha^{-1} (in the absence of manure). For crops receiving pig slurry, savings increased to 40-50 kg N ha^{-1}. On the sandy soils, with the exception of winter barley (recommended > baseline), fertiliser savings were in the range 10-20 kg N ha^{-1} in the absence of manure. Crops that received manure were able to receive reduced N fertiliser inputs of 20-60 kg N ha^{-1}, depending on the type of manure and time of application.

Measure Fa2 was a straightforward 20% decrease in fertiliser applications against baseline (except for winter beans, where no N fertiliser was applied). Because baseline fertiliser levels, on average, were set slightly above the recommended rate, a 20% across the board reduction was equivalent to, approximately, a 15% reduction below recommended rates (in the absence of manure).

Measure Fa5 (adjust fertiliser rates to allow for manure N, no change to the timing of manure applications) yielded results similar to, but not the same as recommendations generated for measure Fa1. This is because the MANNER model was used [10], which allows more sophistication than the tabular version presented in RB209.

Measure Fa5-2 further reduced fertiliser inputs by 20% after allowing for manure N inputs. This would represent a scenario of extreme safety (i.e. compensating for any potential error in the manure nutrient allowance). Fertiliser rates equated to c. 65% of baseline where manure had been applied.

Measures M1 and M2 represent good manure management, in as much as they aimed to shift applications away from the high risk autumn period. However, these scenarios were set such that fertiliser applications were not adjusted against baseline. However, measures M1-M5 and M2-M6 did make allowance for the N 'saved' from leaching. On the clay soils, both of these measures allowed a fertiliser N decrease of c. 80 kg ha^{-1}. For both clay and sandy soils, timing for M5 and M6 produced similar results in terms of fertiliser allowance, suggesting that moving applications to March (M6) was unnecessarily stringent. On the sandy soils, there were again substantial fertiliser savings: 50-130 kg N ha^{-1} (the latter representing the full fertiliser application for the sugar beet crop).

The model approach calculated the soil N supply for each crop. As explained earlier, standard response curves were used, such that the calculated N supply from the different measures allowed an assessment of effects on yield. Table 3.2 and Appendix 2 show that effects on yield were generally small, often nil. In some circumstances, reducing fertiliser inputs increased yields, but again effects were small.

<u>Nitrate loss</u>

The modelled nitrate leaching losses for each measure and point in the rotations are shown in Appendix 2. Data for each rotation are summarised in Table 3.2. Figure 3.1 demonstrates the effects of cropping on nitrate leaching losses. Rainfall increased nitrate losses from the clay soils, but had no effect on the sands (because the soils were completely eluted, even under the 'dry' climate).
The trends in N loss demonstrate the influence of crop on leaching and agree well with the findings of Goulding [30]:

- Clay rotation: losses greatest after oilseed rape and winter beans; losses after winter barley (with oilseed rape) influenced by the autumn N application to oilseed rape.
- Sand rotation: largest losses after potatoes, smallest losses after sugar beet. However, there were elevated losses after the subsequent cereal crop, attributable to N release from the sugar beet tops ('grandfather effect': [31]).

The effects of manure applications can also be seen, as summarised in Figure 3.1. The effects of autumn applications of pig slurry at two points in the rotation can easily be seen, with increases in N loss in the order of 40 (dry) to 80 (wet) kg N ha^{-1}.

Because the model allowed for residual effects of manure build up through the rotations, and because there were more frequent manure applications in the sandy soil rotation, individual manure effects are less easy to discern. Application of broiler litter/pig slurry in the autumn caused large losses of N (140-160 kg ha^{-1}). January applications of FYM also apparently caused increases in nitrate leaching, but some of this can be attributed to the residual effects of previous manure applications. Note also the increases in nitrate leaching in spring wheat after potatoes, even though this crop did not receive manure: this is due to the residual effects from manure applications preceding this crop. The advantage of this modelling approach is that it took account of residual N supply from manure. Impacts of manure are not restricted simply to the year of application.

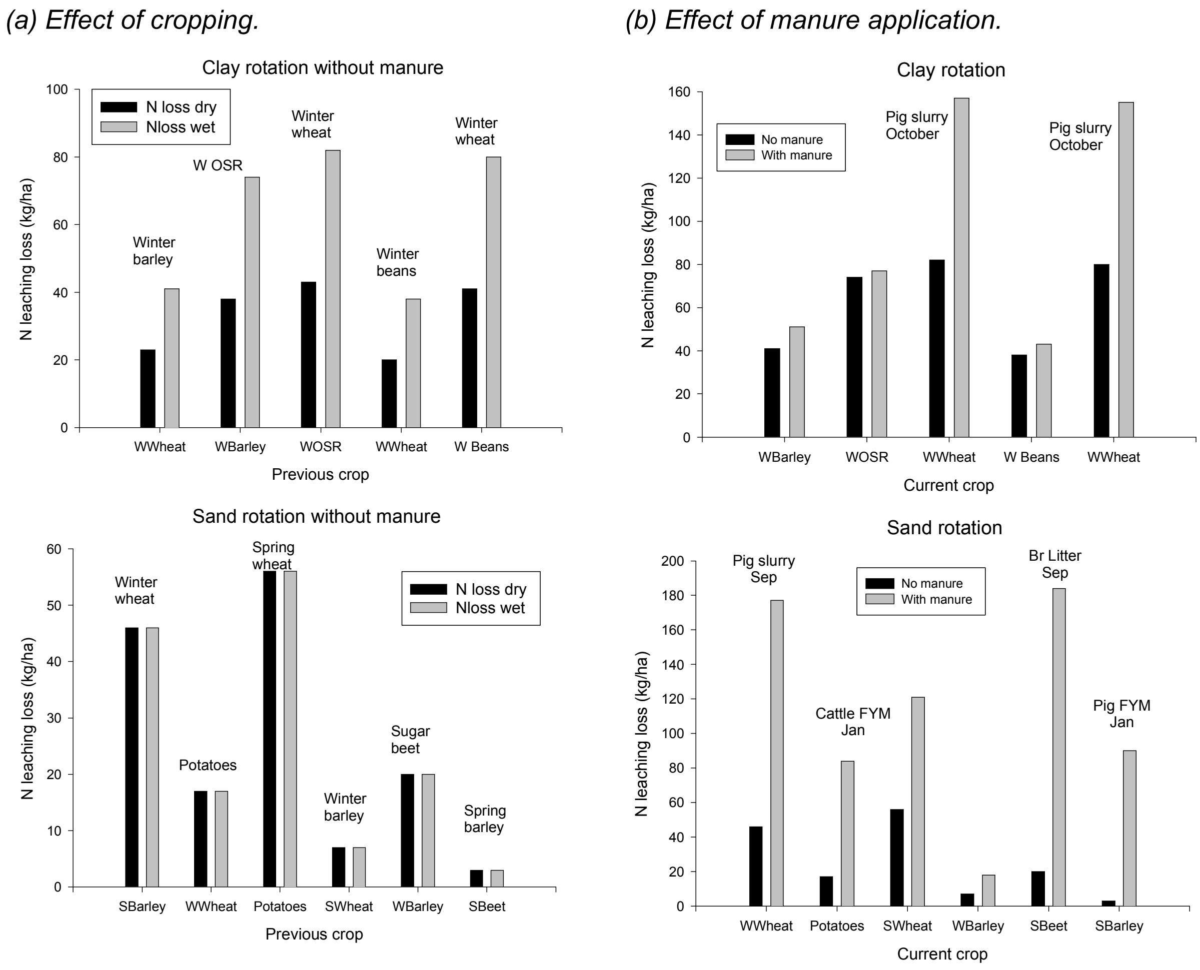

Figure 3.1. Modelled nitrate leaching losses for baseline conditions: (a) as affected by cropping (without manure applications). Labels above bars denote the current crop; (b) as affected by manure application (wet climate only). Labels above bars denote the manure applications.

The effects of measures on nitrate leaching losses can be described thus:
Cover crops before potatoes and beet, in the absence of manure, decreased losses in that year by c. 10 kg N ha^{-1}. This is in general agreement with the literature. Performance of individual cover crops depends on time of establishment and subsequent growing conditions. Reductions in N loss were much greater (30-50 kg N ha^{-1}) when manure was applied, simply because of the larger available N pool for crop uptake. The assumption was that the cover crop was established well enough and early enough to use the applied N.

Measure P4 (set-aside/low N grass) can be a very effective method of decreasing N loss [13], and the modelled data confirm this. Appendix 2 presents the model output for 100% conversion to a nil input system. Table 3.2 scales these effects to 20% conversion. Consequently the effects are less dramatic. Certainly, 100% conversion reduces losses to close to zero. This was noted in the Nitrate Sensitive Area schemes when arable land was converted to unfertilised grass [13]. Long-term set-aside would have similar effects. However, rotational set-aside has been shown to cause substantial leaching where the cover is destroyed in early summer. The model shows that the approach was less effective when manure was applied, demonstrating the systems limited capability to retain N. However, this scenario is rather unlikely (with 100% cover).

Measure Fa2 (20% fertiliser N reduction – below baseline and, in practice, about 15% below recommended N) had little impact on N leaching in the rotations without manure. This would be as expected, given that baseline rates were not excessive, so that any fertiliser decrease affects only the shallow part of the nitrate leaching relationship (Fig. 2.1). However, effects on N loss were much greater where manure had been applied with no previous fertiliser adjustment.

Table 3.2. Summary of reductions in modelled N loss across each rotation for each measure (full data for each crop and each rotation shown in Appendix 2). Values are calculated as Nloss (baseline) – Nloss (measure). Positive values are therefore reductions in N loss.

		Clay				Sand					
		Manure		No		Manure		No		Pigs	
		Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Baseline NO_3-N losses (kg ha^{-1})		*50*	*96*	*33*	*63*	*113*	*113*	*25*	*25*	*184*	*184*
P3	Cover crop on sandy soils	n/a	n/a	n/a	n/a	14	14	4	2	2	2
P4	Premium grass (100%)	36	69	32	61	49	49	23	23	117	117
	Premium grass (20%)	7	14	6	12	10	10	5	5	23	23
Fa1	Improved fertiliser recs	3	6	2	4	6	6	2	2	10	10
Fa2	Reduce N fertiliser by 20%	4	7	3	6	10	10	4	4	6	6
Fa3	No autumn N	5	9	5	9	n/a	n/a	n/a	n/a	n/a	n/a
Fa5	Account for manure	1	0	n/a	n/a	9	7	n/a	n/a	5	2
Fa2 Fa5	Fa5, then decrease N by 20%	4	7	3	6	17	15	4	4	9	8
M1	Manure timing	10	22	n/a	n/a	14	14	n/a	n/a	n/a	n/a
M2	Manure timing	12	24	n/a	n/a	34	34	n/a	n/a	n/a	n/a
M1 M5	Plus account for manure	13	27	n/a	n/a	29	28	n/a	n/a	5	2
M2 M6	Plus account for manure	15	30	n/a	n/a	56	56	n/a	n/a	n/a	n/a
AP2	Reduce pig numbers	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	63	63

Data for Measure Fa1 (recommended rates) are not presented. However, given the effects of measure Fa2 (15% reduction below recommended N), the 5% reduction from measure Fa1 would have smaller effects in the absence of manure. Effects with manure were similar to the effects from measure Fa5.
Measure Fa3 gave good reductions in nitrate leaching on oilseed rape – c. 20-40 kg N ha^{-1}, but less when averaged over the rotation.
Measure Fa5 (account for manure applications in fertiliser recommendations), made only a small difference in N leaching because much of the N had been leached: this measure made no adjustment for timing. Measure Fa2Fa6 decreased leaching further by decreasing fertiliser inputs.
Measures M1 and M2 had a relatively large effect because of the shift from autumn applications. The advantage was further compounded by measures M1M5 and M2M6, which also reduced fertiliser inputs to take account of the saved manure.

<u>Costs</u>

The costs of measures were based on additional costs associated with implementation, net of any savings made as a result of changed practices. Appendix 2 summarises the assumptions made with these costs. As with nitrate leaching losses, costs were averaged over the whole rotation (£ ha^{-1} yr^{-1}). For example, Appendix 2 shows that the cost of cover crop establishment was calculated as approximately £27 ha^{-1}. Two cover crops were grown in the 6-course rotation (before potatoes and beet) = £54. Therefore the annual cost over the rotation was £54 over 6 crops = £9 ha^{-1}.
Table 3.2 shows that the average annual saving in N leached by use of a cover crop was 14 kg ha^{-1} where manure was applied. Thus, this allowed cost to be calculated as £ kg N^{-1} ha^{-1} saved from leaching – in the case of the cover crop this equated to 9/14 = 65p kg N $saved^{-1}$ ha^{-1} (Appendix 2). Negative values in Appendix 2 represent a zero cost to the farmer – or, even, a potential saving.
Cover crops, because of the additional establishment costs, carried a small cost as a measure (Appendix 2). As explained earlier, this would be further exacerbated if the cover crop negatively affected the yield of the following crop. However, we also tested the scenario of the financial implications of a 10% yield increase after beet and potatoes, as was recorded consistently by Shepherd [29]. Not surprisingly, the effects on the finances were positive, with benefits of £4-26 per kg N^{-1} ha^{-1} saved from leaching.

The shape of the fertiliser response curves, as already explained, were such that yield (and, therefore, financial) penalties were small or zero. In some circumstances, because recommended optima in RB209 had been based on higher grain prices and lower fertiliser prices than current, reductions in fertiliser N against recommended had a small positive financial effect (Appendix 2).
Clearly the greatest costs were associated with additional manure storage requirements where autumn applications were shifted to spring. It was also assumed that a shift to spring would require the use of specialist spreading equipment such as a trailing hose or shoe, which would also bear greater spreading costs. Where this shift increases the fertiliser value of the manure, by reducing leaching losses, some of this storage/spreading cost can be offset by reduced fertiliser inputs. Thus the costs are greater for measures M1 and M2, compared with M1M5 and M2M6 (Appendix 2).
Where there is an apparent saving in costs associated with a measure (e.g. saved fertiliser costs, with no yield penalty), some caution is needed when expressing results as £ per kg N^{-1} ha^{-1} saved. For example, measure Fa5 in the clay rotation (wet

climate) saved £7.50 in costs but decreased nitrate loss only by 0.5 kg ha^{-1}. Hence, Appendix 2 shows a potential saving of £15 per kg N^{-1} ha^{-1} saved. In these circumstances, it would be more prudent to allocate zero cost.

Taking land out of production, whilst effective in decreasing nitrate loss (Table 3.2) carries the largest cost per unit N saved (Appendix 2).

Modelling of agricultural systems is a cost-effective method for testing mixtures of measures for reducing nitrate loss – providing that the models are sensitive enough to respond to changes in management. Such an approach allows more flexibility and a wider range of measures to be tested than in field experiments, though the experiments are required to initially develop and test the models.

Arable systems experiments have been used to test some of the measures used in this project. Shepherd & Lord [32] set up a sandy soil rotation, focusing on the use of cover crops, fertiliser policy and changes in timing of cultivation and establishment of the next crop. Over 4 years, losses were decreased from 33 to 18 kg N ha^{-1} by adopting these practices. Losses were greater than the modelled leaching for the sand soil with no manure (33 measured versus 28 kg N ha^{-1} modelled), but the experimental rotation was based on four crops, i.e. with a greater proportion of potatoes (a high leaching risk crop) and a greater proportion of cover crops than in the modelled rotation used in this project. Adjusting, the measured losses to a similar 6 course rotation gives calculated N leaching losses of 33 versus 23 kg N ha^{-1} for the baseline and protective approaches, respectively. This is in general agreement with the modelled scenarios. It also demonstrates, as does Table 3.2, that there is limited scope for decreasing nitrate leaching losses from arable sandland rotations, using simple adjustments to management practices.

Johnson *et al*. [28, 33] tested the effects of cover crops, reduced autumn cultivation, reduced autumn N (for OSR), different cultivation methods and reduced N fertiliser inputs. Adoption of these techniques decreased N losses by, on average, 27 kg N ha^{-1} (from 57 to 30 kg N ha^{-1}). This was a five course rotation, similar to the clay rotation (one less cereal), but on a shallow limestone soil (less retentive than the clay soil used in the modelled system). Again, there was no manure used in this system, and the measures were more extensive than those included in the model runs. However, the measured data are generally in line with the modelled clay rotation.

The measures tested in the project fell, in general terms, into the categories of fertiliser management, manure management, crop management and animal management. There was more scope for measures in rotations that involved manure. Effectiveness of measures is judged in terms of the size of the reduction in N leaching across the rotation, and the cost of applying the measure. Examples of the costs and benefits of the main measures are detailed in Fig 3.2. Those for the other arable rotations are given in Appendix 2. An alternative method is to develop 'cost curves' [25], based on cumulative savings of N leached and cost (e.g. Fig. 3.3, all data shown in Appendix 2). However, this approach assumes an additive benefit from the list of measures. For the arable scenarios tested within this project, the approach is not logical:

- Some of the measures are alternatives to others tested.
- Different measures may impact on the 'same' nitrate.

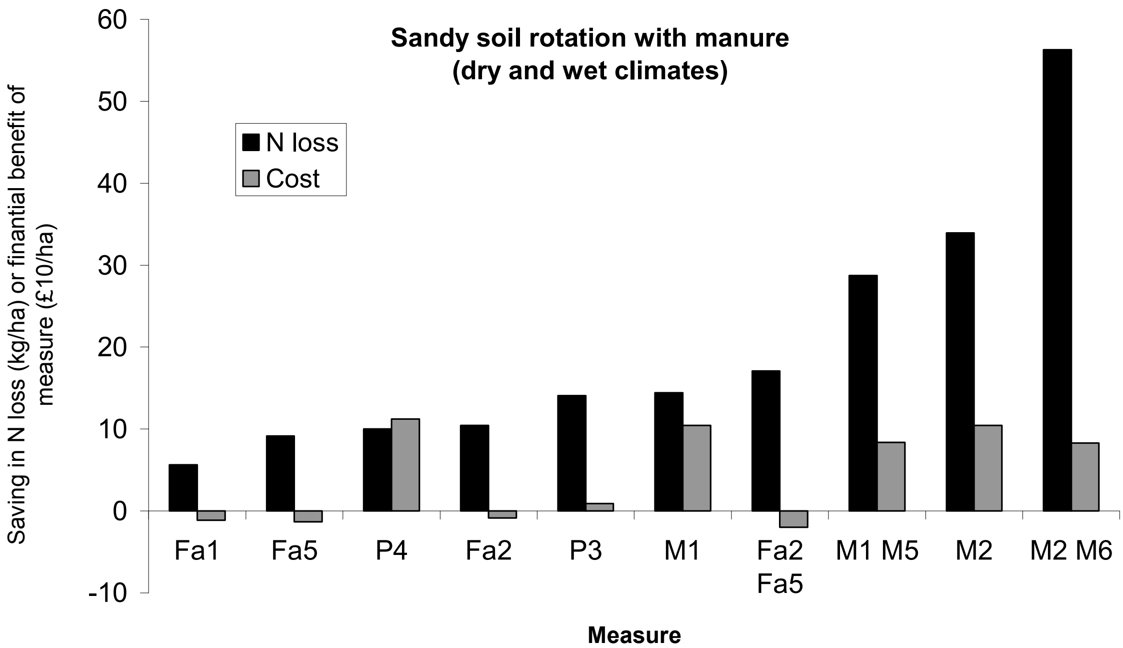

Figure 3.2. Comparison of effectiveness and cost of measures applied to the sandy soil rotation (positive values imply cost).

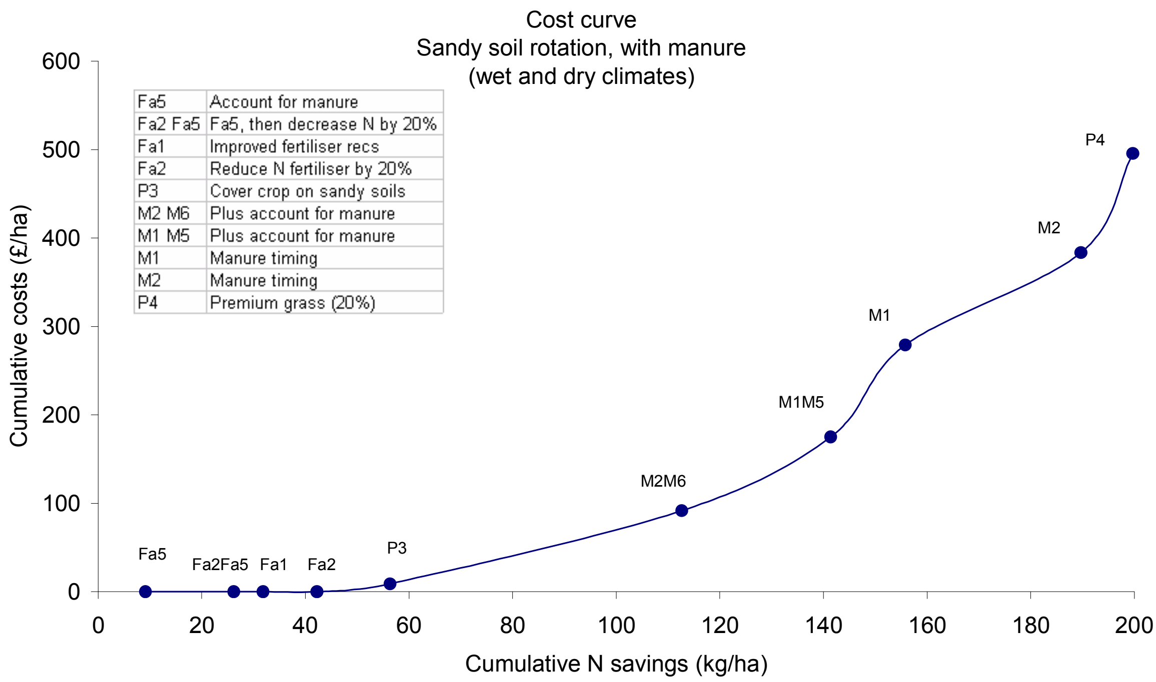

Figure 3.3. Cost curve of mitigation options for sandy soil rotation with manure

Fertiliser management – low or zero cost and reductions up to about 10 kg N ha^{-1}. The calculations in the project showed a benefit to costs, in that the savings in fertiliser outweighed the reductions in yield. This was due to two main reasons:

- Shapes of the response curves were such that small changes around the optimum in fertiliser inputs had small impacts on yield.
- The fertiliser recommendations in RB209 were based on larger grain N prices and smaller N fertiliser prices than is the situation now. Consequently, RB209 recommendations are 10-20 kg ha^{-1} greater than current market prices reflect.

Manure management – there were costs where additional manure storage was required to accommodate shifting manure applications from autumn to spring. Some of these costs were offset when fertiliser applications were adjusted downwards to take account of the increase in available N arising from spring applications of manure (less N leached, compared with autumn applications). A major cause of N loss from manure applications is the failure to make full adjustment in fertiliser applications following manure. This is more of a problem than N losses from autumn applications.

Crop management – Conversion of commercial farmland to extensive permanent grassland greatly reduces nitrate leaching. Conversion of arable land to unfertilised ungrazed green land will reduce nitrate leaching by about 90% in the short to medium term, for the area of land so converted. Within Nitrate Sensitive Areas, arable land converted to extensive unfertilised, ungrazed grassland typically leached less than 5 kg N ha^{-1}, and often less than 1. Conversion of intensive to extensive grassland was also effective, though less dramatic. This option may become more attractive under the range of agri-environmental schemes currently being developed, for example under CAP reform. Prescriptions must include provisions to maximise duration and extent of green cover, and minimise inputs (manures should not be applied to such land). It is likely that over an extended period, nitrate leaching from such land would rise a little, but the benefit in terms of leaching was sustained within Nitrate Sensitive Areas for at least 10 years. Cover crops are also an effective measure. There is a large body of scientific literature to demonstrate at least the short-term effectiveness of cover crops on nitrate loss under UK conditions [29, 33]. Shepherd & Lord [32] consider that cover crops are probably the single most effective short-term control of nitrate leaching in arable rotations. Cover crops were a requirement under the UK Nitrate Sensitive Area Scheme. Cover and catch crops reduced nitrate leaching in most years by about 50% compared to winter cereals [13]. However, to be effective, the cover had to be established early enough (August or September) to take up sufficient N before winter. In short, there has been substantial research undertaken on the use of cover crops under UK conditions, including consideration of the following factors:

- Size of potential benefit, in terms of N leaching loss reduction
- Feasibility of incorporating into the rotation
- Potential effects on following crops
- Potential longer-term effects on N leaching losses.

Animal management – Outdoor pigs are often included in arable rotations on free draining soils of low rainfall and the pigs tend to be moved to cereal stubbles or grass leys in autumn or spring. Stocking rates are typically between 20-30 sows/ha over a total area of approximately 35 ha. A new site is required after 12-24 months. N inputs to outdoor pig farming enterprises can be 625 kg N ha^{-1} at a stocking rate of 14 sows ha^{-1}, with a net surplus of about 500 kg N ha^{-1} [34]. The extent of crop cover affects the leaching risk from this large N surplus, so that grassland is preferred to stubble [35]. However, the problem is maintaining the grass cover, which is grazed by the pigs. Studies in the UK and Denmark have shown that there are strategies to prolong the cover:

- Nose ringing the pigs

- Reduced stocking densities (12-18 sows ha^{-1})
- More frequent rotation of the pigs areas
- Movement of feeding troughs and bedding areas.

There is some financial cost for all of these practices, with nose ringing carrying the smallest cost – though, there are welfare implications.

3.2 Grassland systems

The results of reduced leaching, costs for all the measures evaluated and the implications for cost for the 3 systems are given in Appendix 3. Figure 3.4 shows the data for dairy in Devon of financial benefit vs leaching in units per hectare. An example is given in figure 3.5 of the cost curve for the dairy system in Devon, West Wales and South Cheshire (see Appendix 3 for the rest of the systems).

The most effective measures for reducing leaching in dairy systems were in general:

- Animal-based: Ac1, Ac9, Ac10, Ac11
- Fertiliser based: Fg2, Fg5, Fg8
- Plant-based: G3, G11, G12
- Other and combined options Z

- The animal based measures that resulted in most effective reduction in leaching have to do with 1) reducing the number of animals in the field, and 2) reducing the time the same number of animals are kept outdoors. In the case of Ac1, the efficiency of the measure was due to the combination of reducing the number of animals with a reduction in inorganic fertiliser (see Fg1 below).

The reduction of the grazing period to the extreme; that is zero grazing (Ac11), didn't seem to have produced the expected general effect of a much larger reduction in leaching. Especially in Devon the reduction was larger for Ac10 than Ac11 which seems to contradict what would be expected. NGAUGE for a clay loam poorly drained soil is more sensitive to losses via denitrification rather than leaching. Also the milk prediction in the baseline was slightly larger for grazing than housing. This means that being indoors all year the net milk produced is less than if the cows had been outdoors for some of the time. In this case, more N goes to excreta and the leaching is larger.

Reducing the number of animals, but changing to more productive ones did not give an effect in leaching. This was due to the fact that the inputs/outputs of the system did not change.

The less effective ones were the measures that involve manipulating the diet (Ac2-Ac6). Among these, reducing CP intake was better (Ac2).

- The fertiliser based measures that were more effective were the ones that corrected N application due to manure, S and K soil deficiency and time of the year. Decreasing inorganic fertiliser as a single measure (Fg1) was not as effective, we already mention above the better results obtained when used in combination with a reduction in stocking rate. The same applies for Fg6, as it was applied as a single reduction in inorganic fertiliser.
- The plant based measures evaluated showed that changing to grass/clover swards and other forages (G11) was the most effective measure in Devon and West Wales but not in Cheshire. The other measures (G3, G6 and G12) were less effective or even increased leaching (see G12 Devon).
- The manures based measures (M1 and M1a) were less effective in general, and especially M1 does not consider the total effect of the measure, as there will be some manure exported from the farm that will have an impact elsewhere. There were large differences between locations, mainly due to soil type. For example South Cheshire, having similar temperature and slightly less rainfall than West Wales, produced much larger leaching values, mainly due to its moderately drained loam soil, as compared to the poorly drained clay loam in the Welsh location. Leaching in West Wales was in general larger than that in Devon, due to the larger rainfall, although when the reduction in leaching was small, differences between these two locations seemed to be smaller. In summary, the general trend was leaching was larger in South Cheshire>West Wales>Devon. The effectiveness of the measures also changed with location, as Figures 3.4 and equivalent figures in Appendix 3 show, with leaching reductions being larger for South Cheshire (up to 23.2 kg N ha^{-1} y^{-1}) than West Wales (up to 16.5 kg N ha^{-1} y^{-1}), and this one larger than Devon (up to 9.1 kg N ha^{-1} y^{-1}). The NVZ restrictions were also effective in reducing leaching.

In order to include the product in the estimate of costs, a conversion from N produced to a profitable product had to be made. The model produces an output of kg N ha^{-1} that, for dairy was converted into milk, assuming the N content in milk is the same but the volume changes.

The measure that implied the largest cost per hectare was Ac11 at all the locations. This was due to an increase in income through larger product output. The model assumed that the N in the product (explained above) was larger when the animals were kept indoors than when there was grazing. This measure assumes that the animals are kept indoors all year.

Measures Ac1, Ac9, Ac10 were also costly (per hectare) as well as G12. These were also effective in reducing leaching.

The costs per unit N reduced were less than £50 kg N $reduced^{-1}$ for all measures except for Ac11 and Ac2 mainly due to loss of income from less product output. G12 increased leaching in Devon so there is no sense in reporting a cost for this measure for this particular location.

The measures that gave positive cost values were set as zero cost and the absolute values for the rest of the measures were sorted in ascending order. From these the cumulative costs (£ ha^{-1}) and leaching reduction (£ kg N $reduced^{-1}$) were plotted to produce a cost curve (see Figure 3.5). This figure shows that the reduction in leaching was larger for the South Cheshire location than West Wales and this larger than Devon. This demonstrates that the wetter clay soil had less potential for reducing leaching as well as producing the lower costs for the application of the measures.

The most effective measures for the beef system were: animal based measures, Ac1 and Ac10, fertiliser based measure Fg8 and Fg6 and plant based measures G3 and G11. G6 proved to be ineffective in reducing leaching for the two locations studied so will not be considered in the discussion. There were differences between locations but reduction in leaching was always less than 6.1 kg N ha^{-1} y^{-1}. For the costing, the output of the model in kg N ha^{-1} was converted into beef product (meat) by following the equation 2.3 kg N = 100 kg liveweight gain ha^{-1} (M. Gibb pers. comm.), the same was used for sheep.

Costs were always less than £50 per unit N reduced (£ kg N $reduced^{-1}$). The costs per unit area were, except for measure Ac10 also less than £50, in general much less than the measures applied to the dairy systems. The cost curves for the beef systems showed that there were little differences between locations, with Co Durham being slightly more effective in reducing leaching above 18 kg N reduced ha^{-1}.

In the sheep system, leaching saved was less than 4.2 kg N ha^{-1}. Measures G3 and Ac1 were effective in reducing leaching and in the case of G3 there isn't a finantial loss for the farmer. Fg8 increased leaching so will not be included in the discussion. The cost curves for the sheep systems showed that there were little differences between locations, with measures applied in Co Durham being slightly less effective in reducing leaching.

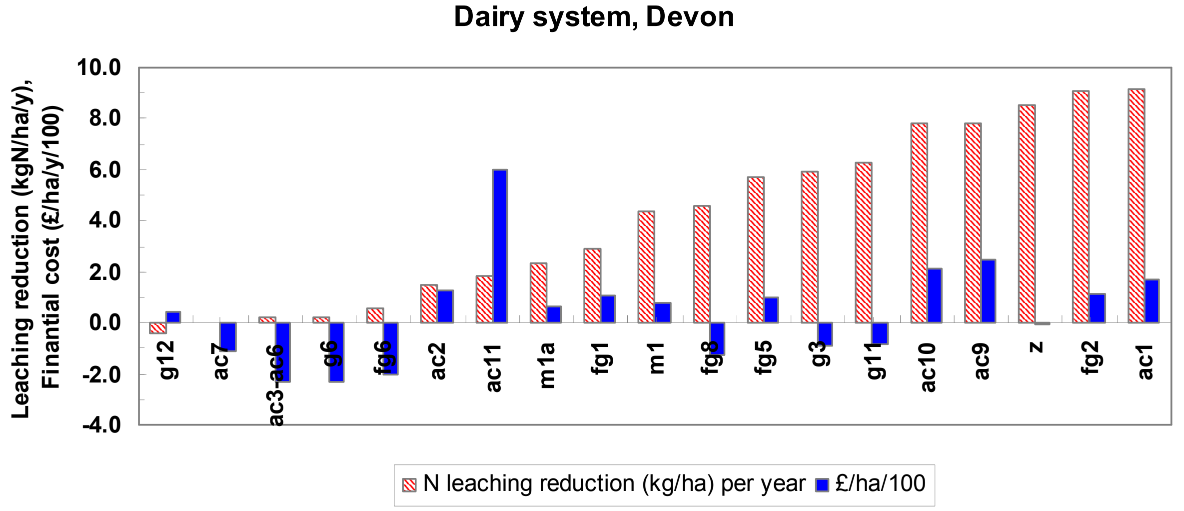

Figure 3.4. Results of N leaching (kg N ha^{-1} y^{-1}) and cost of the application of mitigation measures (£ ha^{-1} y^{-1}) for dairy system in Devon

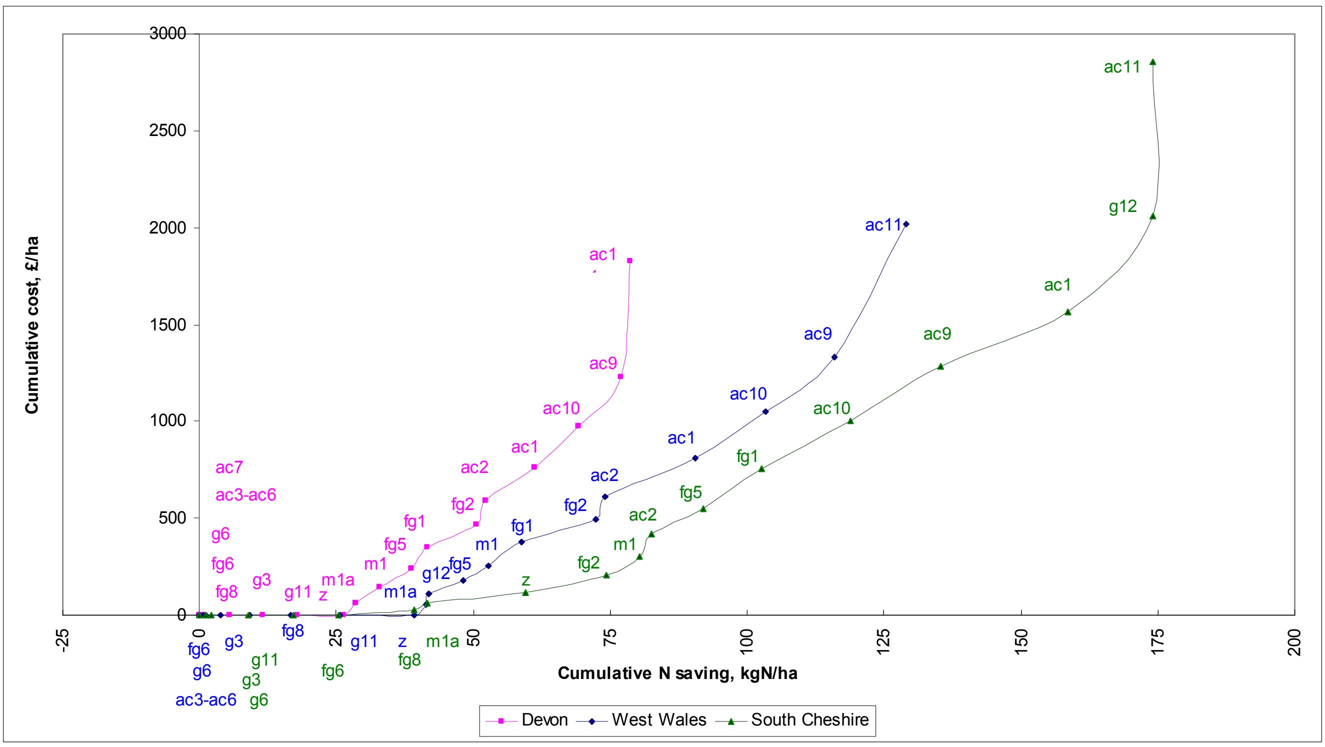

Figure 3.5. Cost curves of mitigation options for dairy systems

4. CONCLUSIONS AND MAIN IMPLICATIONS

4.1 Arable systems

- Many of the approaches to decreasing nitrate loss from arable systems carried only a small cost or provided a cost benefit to the farmer. These mainly revolved around better use of fertilisers, emphasising the need for good fertiliser planning.
- Adjusting fertiliser rates to below the currently published recommendation (RB209) often showed a small financial benefit. This is because current fertiliser and produce prices have shifted the economic optimum downwards. Providing this information to farmers is a quick way of affecting nitrate leaching.
- However, this does not address the issue of fertilising for quality (e.g. grain protein, baking potatoes), where crops are 'over-fertilised' (i.e. above requirements simply for yield) to achieve various standards. This was not tackled in this project.
- The modelling showed that only small impacts could be achieved in arable rotations without manures, particularly on the sandy soils.
- Rotations with manure had greater nitrate leaching losses than those without manure – and offered greater scope for decreasing losses. Nevertheless, even by adapting best practices, nitrate losses will inevitably be greater when manure is used in systems.
- Taking land out of production is an effective method of decreasing nitrate losses from that land. Overall effects in a catchment or on a farm depend on the proportion of land removed. However, there is a substantial cost to this approach: although this was the single most effective method of decreasing nitrate losses in NSAs, farmers were compensated.

4.2 Grassland systems

- The most effective measures to reduce leaching for the dairy system were in general the ones that involved reducing stocking rates, the time the animals are kept outdoors throughout the year, improving the timing of inorganic fertiliser application and accounting for manure N. Manipulation of grass measures, and implementation of NVZ regulations were also effective but less so than those above.
- There were regional differences for the dairy system in the effectiveness of the measures in reducing leaching with the extent of reduction being ordered as Cheshire>West Wales>Devon.
- The costs of the application of the measures were in general below £50/kgN reduced. The larger costs were estimated for Ac2 and Ac11 (reduce N surplus in the diet and adopt zero grazing).
- The most effective measures to reduce leaching for the beef system were in general the ones that involved reducing the time the animals spent outdoors. Next most effective were those involving grass management (eg. G3).
- There were very little differences in the effectiveness of the measures applied in the beef system in the two locations evaluated.
- The most effective measures in beef (except for Ac10) were associated with the smallest costs, for example Fg8, G3, G11.
- The most effective measures to reduce leaching for the sheep system were Ac1 and G3; that is, reducing stocking rate by 20% and reseeding in spring.
- There were no differences between locations in the effectiveness of the measures in the sheep system.
- The costs for implementation in the sheep system were relatively low compared to the beef and dairy systems.

Implementation of the most effective measures involving reduced stocking rates and time spent grazing were all associated with relatively high costs (£7-£20 kg N reduced^{-1} ha^{-1} y^{-1}). Moreover, implementation of zero grazing had the highest costs (c. £50 kg N reduced^{-1} ha^{-1} y^{-1}) and this was due to the assumption made that machines to cut and carry fresh forage would have to be bought in, whereas for the baseline scenario, a contractor would have been used to cut silage 2 times a year. Clearly, any reduction in animal numbers and grazing time would need to be compensated by income derived from a more valuable product and/or greater environmental benefits, due to for example, increased biodiversity or landscape aesthetics on the farm. It is unlikely that reduction in grazing would result in high value products because this would contain fewer healthy constituents and would have reduced perceived animal welfare scores. There are a number of measures, however, involving plant and manure management that were relatively effective but have low or zero cost of implementation. These should be the measures to consider first when moving from the baseline situation. For example, selection of high sugar grasses and changing to grass clover swards would all be relatively cheap to implement and would reduce leaching between 0.8 and 6.2 kg N ha^{-1} y^{-1}. Greater reduction maybe duable by implementation of multiple measures. Two other effective strategies were optimisation of fertiliser and accounting for nitrogen in manures (Fg6 and Fg5), both of which would have quite low cost for implementation. However, reducing fertiliser input by 20% (Fg1) was not predicted to be cost effective as no reduction in animal numbers was assumed which led to poor animal nutrition and output.

Recommendations for future work

This project shows that we generally have a good understanding of nitrate leaching losses and their potential mitigation, and that we are able to model these effects. However, the project has also highlighted where further work is necessary:

1. Identification of the most practical and effective ways of implementing the most cost-effective measures.
2. Assessment of the impacts of degrees of success with implementation of cost-effective measures at the catchment scale in real catchments.
3. Quantification of the effects of implementation of cost-effective measures on pollution swapping at a range of scales.

Outputs from the project

1. In fulfilment of milestone 3a in the proposal, a demonstration of the findings from the study has been made at a workshop for farmers on compliance with the Nitrate Vulnerable Zone legislation held in Launceston in March 2005.
2. Information from the project, particularly the review of mitigation methods, is already being used by Defra policy groups (WQD, CSF, NMU).
3. The main findings will be posted on the IGER NUTMOG website and on the ADAS website.
4. The Review and Final Report will be posted on the DEFRA website.
5. Findings will be presented at the Royal Welsh show and the Royal Show.
6. Scientific papers planned for submission in summer 2005.

References to published material

9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

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