

Mitigation Method-Centric Framework for Evaluating Cost-Effectiveness

Defra Project WQ0106 (Module 3)

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Executive Summary

The Defra Nutrient Management Programme aims to reduce the nutrient over-supply in the ecosystem through maximising the efficiency of the nutrient cycle on farms and thereby reducing emissions of pollutants to air and water. An important aspect of this programme is the development of a quantitative understanding of the impacts that potential pollution mitigation methods may have on multiple pollutants. Under Defra project WQ0106, the 'User Manual' of diffuse pollution methods (Cuttle et al., 2006) is being updated to include an extended list of mitigation methods, and impacts on gaseous emissions (ammonia, nitrous oxide and methane) in addition to losses to water (Newell-Price et al., 2009). The aim of this project was to develop a method-centric framework (**FARMS**COPER – **FARM** **S**cale **O**ptimisation of **P**ollutant **E**mission **R**eductions) which could be used to assess the impact of these farm pollution control options on multiple pollutants. The development of this framework required:

- The estimation of diffuse pollutant losses at the farm scale
- A method to quantify the cost and effectiveness of one of more mitigation methods
- A method to identify optimal sets of mitigation methods

The mitigation methods included in the framework were taken from the revised 'User Guide' of methods (Newell-Price et al., 2009), and generally represented potential for improved practice within existing farm systems rather than adoption of novel systems or technology. A total of 77 methods were incorporated, each characterised for their impact on nitrate, phosphorus, sediment, nitrous oxide, methane, ammonia and pesticide losses. The effects of the mitigation methods were estimated from literature, modelling and expert judgement and represented as a percentage reduction against a specific set of coordinates representing differing sources, areas and delivery pathways on representative model farms. Livestock, cropping, fertiliser and manure management practices on these model farms were derived from literature and national stratified survey data. Pollutant losses on the model farms were calculated for a range of soil types and climates using existing policy models, with the losses apportioned into the same coordinates used for targeting mitigation methods.

The framework created produces pollutant losses for the different farm types, under different environmental conditions, such that the source apportionment can be investigated and the losses from one farm readily compared with those of another. The impacts of different combinations of mitigation methods can be evaluated against different farms to compare levels of pollution reduction that can be achieved, and the cost-effectiveness of achieving this on different farm types or under different environmental conditions investigated.

The framework implemented a novel genetic algorithm model to search for pareto-optimal combinations of mitigation methods. This generates a large number of potential solutions to pollution control which can be analysed to provide insight into the range of possibilities.

The framework also allows for the effects of uncertainty in pollutant losses and mitigation method impacts to be investigated, both demonstrating the potential bounds of reduction that could be realised following the implementation of a set of mitigation methods and ensuring that only suites of methods with a high probability of meeting any specified targets are selected through the optimisation process.

A wide range of analysis is possible using the framework created. A selection of results were produced in this report to demonstrate the functionality of the framework and to provide an insight into the levels of pollution reduction that could potentially be achieved on the different farm types, under different environmental conditions. Under a climate and soil type typical of much of central and eastern England, the results from FARMSCOPER suggest that reductions in phosphorus pollution of over 60% are possible on most farm types and close to 50% for sediment and pesticides on all farm types. In theory, reductions of nitrate of up to 45%, ammonia up to 60% and nitrous oxide up to 35% could potentially be achieved, but there was much greater variation between farm types. These reductions, achieved through application of all 77 methods available in the framework, resulted in substantial costs for some farms of up to £45,000 per annum, although efficient use of manure and fertiliser resulted in savings being made on other farm types. However, the implementation of all methods is impractical on any given farm.

1. Introduction

This report summarises technical work for the Defra Water Quality Division to provide a framework for the assessment of the potential to reduce agricultural emissions of pollutants to air and water at the farm scale. The work links and builds upon the results of Defra projects WQ0106: Cost and Effectiveness of Policy Instruments; WT0706CSF: Benefits and Pollution Swapping; SFF0601: Business as Usual III; and WT0743CSF: Evaluating the Extent of Agricultural Phosphorus Losses across Wales. In particular, this project develops the farm assessments of pollutant loss and mitigation method effect developed in project WQ0106 Module 5 (revised 'User Guide' of mitigation methods; Newell-Price et al., 2009) by providing a clear framework with which to assess the pollution occurring on a farm and the impacts of single or multiple mitigation methods, using the methodology developed under project WT0743CSF (Anthony et al., 2008).

For a period of time, this project ran concurrently with WQ0106 Module 6, which assessed the impact of mitigation methods at a national and river basin district scale. As a result, there is some overlap in the methodology of the two projects, with this project building upon the methodology used for Module 6 by increasing the apportionment of losses, refining the targeting of the mitigation method impacts and costs and developing the model-based tool supplied which enables a quick and easy assessment of pollution and potential control at the farm scale. For clarity, some parts of the report for WQ0106 Module 6 are repeated within this report.

1.1. Background

The Defra Nutrient Management Programme aims to reduce the nutrient over-supply in the ecosystem through maximising the efficiency of the nutrient cycle on farms and thereby reducing emissions of pollutants to air and water. The programme will achieve this by improving the coordination of the many areas of diffuse pollutant control work within Defra. An important aspect of this coordination is the development of a quantitative understanding of the impacts that potential pollution mitigation methods may have on multiple pollutants.

Work completed by ADAS under Defra project WQ0106 included the use of a model framework to assess the impact of farm pollution control options on nutrient and sediment loss in response to a target for phosphorus loadings (Anthony, 2006; Anthony and Collins, 2006). The work demonstrated that some methods that control phosphorus losses can also reduce sediment and nitrate losses, and that the overall cost of pollution control could be minimised by careful selection of a suite of methods. This work built upon the characterisation of potential mitigation methods in the 'User Manual' of diffuse pollution methods (Cuttle et al., 2006). The manual is now being updated as the 'User Guide' that includes an extended list of mitigation methods, and impacts on gaseous emissions (ammonia, nitrous oxide and methane) in addition to losses to water (Newell-Price et al., 2009).

The policy targets for the reduction of diffuse pollutant losses to air and water vary by pollutant. The United Kingdom is legally bound to reduce greenhouse

gas emissions by 80% by 2050, and to reduce CO₂ emissions by 26% by 2020 (Climate Change Act, 2008). The United Kingdom is also required to reduce ammonia emissions to 297 kt yr⁻¹ under the Gothenburg Protocol and National Emission Ceilings Directive by 2010. The Nitrates Directive (81/676/EEC) sets a standard of 50 mg l⁻¹ NO₃ for nitrate concentrations in surface and ground waters. The UK implementation of the Water Framework Directive (2000/60/EC) sets phosphorus concentration standards of 50 to 120 ug l⁻¹ for good ecological status, and the Freshwater Fish Directive (78/659/EC) sets a guideline target of 25 mg l⁻¹ suspended solids for salmonid and cyprinid waters. Achieving these quality standards will require wide ranging reductions in pollutant loads from the agricultural sector. The modelling framework built within this project is suitable for assessing the cost and effectiveness of mitigation methods against multiple pollutants and multiple targets, and thus assessing the potential synergies between mitigation methods selected to target water and air pollutants.

1.2. Objectives

The aim of this project was to develop a method-centric framework that enabled:

- The estimation of diffuse pollutant loss at the farm scale for:
 - Nitrate
 - Phosphorus
 - Sediment
 - Ammonia
 - Methane
 - Nitrous Oxide
 - Plant Protection Products
 - BOD
 - FIOs
- The quantification of the cost and effectiveness of one or more mitigation methods
- The identification of optimal sets of mitigation methods

This was to be achieved through the creation of representative farm types, for which the framework would calculate the pollutant losses and method impacts

Sections 2 and 3 of this report present an overview of the approach and the environment and agricultural data used as the baseline for this work. Section 4 describes the pollutant loss models, Section 5 describes the candidate mitigation methods and Section 6 the algorithm for identifying the most cost effective combinations of methods. Section 7 describes the features of the framework developed under this project (a more detailed user guide is found in Appendix I) and Section 8 presents some results generated with the framework to show baseline pollutant losses and potential costs and effects of mitigation method implementation for a range of situations. Finally, Section 9

concludes with a brief discussion about the framework, its potential uses and the initial results presented.

2. General Methodology

Anthony (2006) and Anthony et al. (2008) demonstrated a generic methodology for calculating the cost and effect of mitigation methods for control of diffuse agricultural pollution. The methodology involved the derivation of export coefficients from the output of mechanistic models applied to model farm systems that are representative of typical practice. The export coefficients express the pollutant loss as a linear function of the potential pollutant input to the farm system in the form of fertiliser and excreta. In a deviation from typical export coefficient models, losses are also expressed as a function of the land area where it is necessary to represent pollutant sources that are intrinsic or respond slowly to reducing inputs. The export coefficients are derived by applying the mechanistic models to a large number of scenarios representative of the national range of environment conditions. Area-weighted average coefficients are calculated for types of soil or climate so that the export coefficients represent a statistical summary of potential losses across a large area.

The mechanistic models supporting the export coefficients are used to explicitly disaggregate the total pollutant loss between the different coordinates (e.g. source; area; pathway: Table 1) on a farm, based on the detailed management assumptions for each model farm system. The effect of a potential mitigation method is then expressed as a percentage reduction in the pollutant loss from a specific set of coordinates. Hence it is possible to represent the targeted impact of mitigation methods. The effect values are derived from the literature, from limited field data and from expert judgement, along with estimates of implementation cost. The net cost and effect of a combination of mitigation methods depends on the extent to which they target the same source coordinates.

A library of mitigation methods is incorporated within the framework to enable the calculation of effect of suites of different mitigation methods on pollutant losses from the farm and the cost of their implementation. Computer tools have been developed that use iterative algorithms to calculate the most cost-effective set of mitigation methods to achieve a target pollutant reduction. The optimal set of methods (for e.g. a policy instrument) could in principle be found by simulating all possible combinations of mitigation methods, but this is a numerically intensive task that scales exponentially with the number of mitigation methods (It is also not necessarily sensitive to the practicability or feasibility of implementing methods on any particular farm). Existing frameworks have therefore minimised the computing resource by calculating a cost curve for either a single pollutant (Anthony et al., 2008) or a weighted sum of pollutants (Anthony, 2006). However, this single-objective approach requires that a relative value or weight can be assigned to each pollutant at the outset of the computation. It is then possible that the optimal policy instrument will be over-looked as we pre-emptively constrain the optimisation process.

This project has therefore adopted a proper multi-objective methodology to identify optimal policy instruments. It is derived from the Non-Dominated Sorting Genetic Algorithm (NSGA-II; Deb et al., 2001) and uses principles of

evolution to simultaneously optimise on all objectives and minimise the computing resource. The methodology identifies the pareto-optimal front of non-dominated solutions. A solution or combination of mitigation methods dominates another solution if it is superior or equal in all objectives but at least superior in one objective. The complete set of non-dominated solutions represents the best available solutions for achieving each objective. After calculation, the set can be sieved to identify the solutions that satisfy a range of constraints. It is therefore possible to delay the weighting of objectives (such as the relative worth of reducing phosphorus versus nitrate pollution) until all of the possible outcomes have been reviewed.

2.1. Coordinate System

To enable the targeting of the mitigation methods, the pollutant losses were disaggregated according to the system shown in Table 1. The coordinates for any pollutant loss can be constructed using a logical sequence of components from the system e.g.:

- *Dissolved* in *Runoff* from *Pig Slurry* applied to *Arable* land in the *Short* term
- *Particulate Soil* loss in *Preferential* flow from *Grass* in the *Medium* term
- *Gaseous* losses from *Enteric* emissions from *Dairy Housing* in the *Short* term

The impacts of a mitigation method can then be expressed against the individual coordinates, which allows for highly specific targeting. Thus, rather than just saying, for example, that a mitigation method reduces all nitrate losses by 30%, the impacts of the method could be targeted at losses from leaching of soil nitrate only and not incidental losses of fertilisers and manures, or losses in runoff or preferential flow.

There is some redundancy in the system (e.g. all losses in the gaseous pathway will be as a gas; everything from the soil source will be of soil type), but this enables all losses to be a function of each of the six components of the coordinate system.

The meanings of the timescales components for all pollutant except nitrous oxide are:

- Short timescale losses are incidental, typically occurring within a month of excretion or manure / fertiliser application
- Medium timescale losses typically occur within a year (e.g. over-winter losses for nitrate)
- Long timescale losses represent those from the long term build up in stores e.g. nitrate in the soil from gradual mineralisation of soil organic matter built up by past manure applications

Currently, only nitrate losses are assumed to have any medium and long term impact, and all losses of methane, ammonia, pesticides and sediment are considered to be incidental or short term. Thus the modelling does not represent changes to e.g. soil P status over time.

For nitrous oxide, the timescale components have a slightly different meaning:

- Short timescale losses represent immediate loss of nitrous oxide from the decomposition of crop residues, from nitrogen fixation, from manure and fertiliser applications and from excreta on the steading (i.e. nitrification and de-nitrification)
- Medium timescale losses are from indirect atmospheric deposition
- Long timescale losses are from the de-nitrification of leached nitrate in water courses

The following points explain the other features of the system:

- Dirty water is associated with the animals held on the hard standings on which the water was generated.
- Field storage for FYM represents field manure heaps, whereas steading storage represents manure heaps on an impermeable concrete base.
- Field storage for slurry represents an earth banked lagoon, steading storage for slurry represents a steel tank.
- Direct losses are from excretion or application directly into water courses, where there is no need for another delivery pathway
- Water based pollution from non-field areas is always classified as runoff

Table 1 Coordinate system used for disaggregation of pollutant losses

Source	Area	Pathway	Type	Timescale	Form
Dairy	Arable	Runoff	Soil	Short	Particulate
Beef	Grass	Preferential	Fertiliser	Medium	Dissolved
Sheep	Rough	Leaching	FYM	Long	Gas
Pigs	Yards	Gaseous	Slurry		
Poultry	Housing	Direct	Litter		
Chemical	Tracks		Voided		
Soil	Fords		Enteric		
	Field Storage		Dirty Water		
	Steading Storage		PPPs		

Because individual mitigation methods frequently target a group of coordinates, some logical shorthand is used to simplify the description of mitigation method impacts and costs. Aside from 'All' meaning everything under a given component, some other shorthand is listed in Table 2.

Table 2 Short hand for multiple coordinates

Shorthand	Full Coordinates
AllManure	FYM Slurry Litter
AllAnimal	FYM Slurry Litter Voided Enteric
AllField	Arable Grass Rough Tracks Fords
AllNonField	Yards Housing Steading Storage Field Storage

2.2. Environment Data

The mechanistic models selected for calculating emissions of phosphorus, sediment and nitrate water were applied to agricultural data across England and Wales, using statistical summaries of soil data and climate data derived from national inventories at a spatial scale of 1 km². The results of these calculations were then area-weighted to create average loss values for generic soil types and climate zones (see Section 4).

2.3. Climate Data

Climate data for the standard period 1961 to 1990 were obtained from the Climate Research Unit at the University of East Anglia (Barrow et al., 1993). Six climate zones were defined based on the range of annual average rainfall, in order to provide sufficient graduation between the drier eastern arable areas and the wetter western more grassland areas (Figure 1).

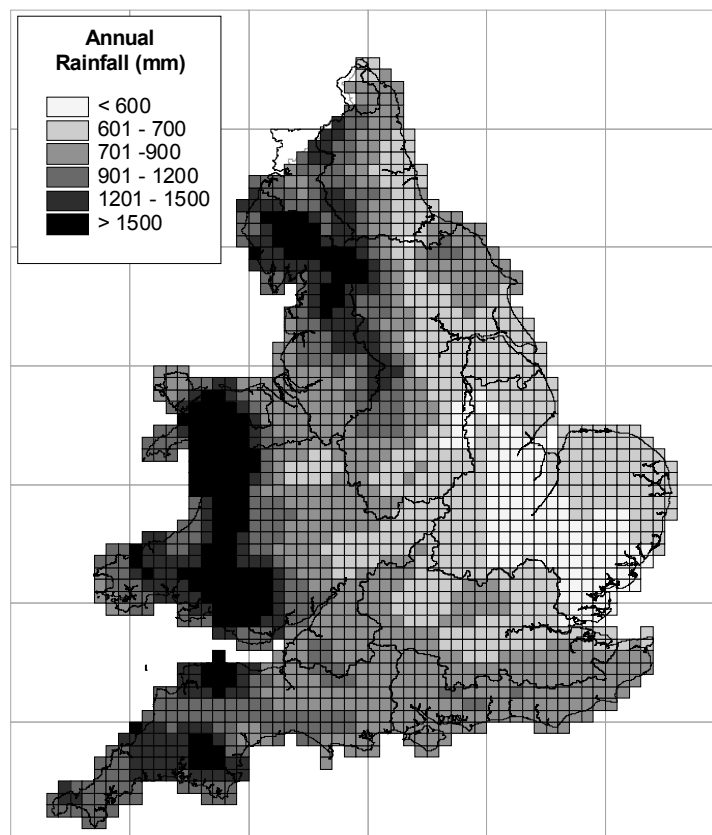


Figure 1 Climate zones defined by ranges of average annual rainfall (mm) for the period 1961-1990 across England and Wales

2.4. Soils Data

The National Soils Resources Institute (NSRI) at Cranfield University provided soils data for input to the mechanistic loss models under a Defra contractor licence. The input data required for the pollutant models were the particle size distribution (percentage sand, silt and clay), organic matter content and bulk density of the dominant soil series at every 1 km² across England and Wales. The soils information also included the Hydrology of Soil Types (HOST) class (Boorman et al., 1995) from which the models determined the relative importance of surface and subsurface flow paths. This was critical for assessing the potential impact of mitigation methods that were effective against only one pathway.

To simplify the development of the pollutant export coefficients, three representative soil groups were defined based on the likelihood of having artificial under-drainage; those not requiring any under-drainage; those requiring under-drainage for arable use and those requiring under-drainage for both arable and grassland (Figure 2). This separated the individual soil series into a group that was generally regarded as free draining, a group that was slowly permeable or moderately impermeable and a group that was impermeable. The need for under-drainage was estimated based on the soil HOST class using rules from the PSYCHIC model (Davison et al., 2008). The mechanistic pollutant loss models were run using the attributes of each and every soil series within a soil group, and the results area weighted to generate a single export coefficient for each drainage group (for each climate zone).

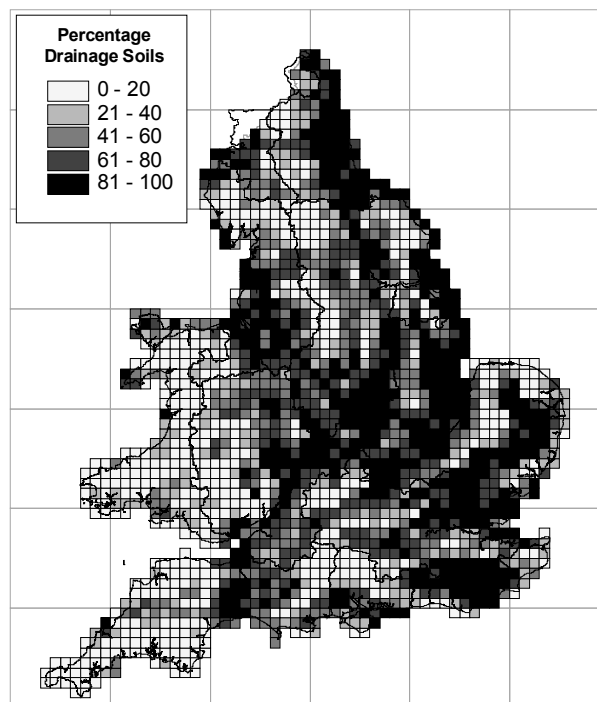


Figure 2 Percentage of agricultural land location on soils that would normally be expected to have artificial under-drainage when supporting arable cultivation

3. Agricultural Land Use and Practice (Model Farms)

Model farm descriptions were used as input to field scale mechanistic pollutant models to calculate representative pollutant loadings in the absence of mitigation methods (referred to as baseline scenario losses). The baseline scenario results over-estimate present day actual pollutant load as many mitigation methods are already part implemented by farmers in response to existing policy instruments. Calculated pollutant loads that took account of present day method implementation are referred to as prior implementation scenario losses. The assumptions about prior implementation of mitigation methods are a key aspect of the definition of agricultural practice.

The calculation of baseline pollutant losses from agricultural land using field scale mechanistic models required an explicit definition of standard agricultural practice. This was based on the representative model farm systems developed to support the revised 'User Manual' (now 'User Guide') of mitigation methods (Newell-Price et al., 2009). The detailed assumptions about farm structure and practice on the model farm systems are given in Newell-Price et al. (2009). A summary of the data is presented below.

3.1. Crop Areas and Stock Numbers

The representative model farm systems were based on the nine 'Robust Farm Types' (RFT) used by the Farm Business Survey and defined by the dominant source of revenue (MAFF, 1993). The farm systems excluded the 'Other' RFT that defines holdings that either do not fit in well with mainstream agriculture or are of limited economic importance (Table 3).

Table 3 Representative model farm systems defined in the 'User Guide' of mitigation methods project, and mapping to the Defra 'Robust Farm Types' (Newell-Price et al., 2009).

'User Guide' Farm Type	'Robust Farm Type'
Dairy	Specialist Dairy
LFA - Grazing Livestock	LFA - Grazing Livestock
Lowland - Grazing Livestock	Lowland - Grazing Livestock
Mixed	Mixed
Winter Combinable Crops	Specialist Cereal
Mixed Combinable Crops	Specialist Cereal
Roots & Combinable	General
Indoor Pig	Specialist Pig
Outdoor Pig	Specialist Pig
Poultry	Specialist Poultry
Horticulture	Horticulture

The model farm sizes (total arable crop and grass area) were based on the average farm areas given in the Farm Business Survey for 2006, for England only. The farms surveyed by the Farm Business Survey are generally larger than the average census farm as the survey excludes minor holdings. The proportions of the land area occupied by each crop type and the stocking densities of each livestock type were derived from the Defra June Agricultural Census for 2004 for each farm type. Multiplying these ratios by the total farm

areas derived the actual crop areas and stock counts on the model farms. The crop areas and stock numbers were then adjusted pro rata so that the England totals across all farm types agreed with the published census data. This accounted for the relatively small land area and livestock count found on the 'Other' RFT that had been discarded.

In order that the model farms had physically realistic crop rotations and livestock numbers a number of expert adjustments were made to the average farm statistics. For example, small numbers of pigs and poultry were removed from the specialist 'Dairy' farm and the total numbers of cattle were adjusted to achieve a typical economic stocking rate. These adjustments were necessary to convert a statistical farm definition, averaged across all surveyed farms of a type, into a simpler and more easily recognised farm definition suitable for use with the public version of the 'User Guide' of mitigation methods (Newell-Price et al., 2009).

This project introduced an 'Outdoor Pig' farm category, and a sub-classification of the 'Combinable Crops' farm ('Mixed – Spring and Winter' and 'Winter') that are not explicitly represented in the Farm Business Survey.

The Indoor Pig and Poultry farm types had no associated land on which to spread the manure produced by the animals. Instead, versions of the Combinable Crop farms and Roots & Combinable Crop farm were created which imported the manures from these livestock farms. The 'Combinable Crop with Pig Manure' farm types imported the manure from one Indoor Pig farm; a single 'Roots & Combinable Crop with Poultry Manure' farm type was assumed to import half of the manure produced on one Poultry farm. This resulted in approximately 23 kT manure total N being imported on to each farm.

Table 4 Summary of crop areas (ha) on each of the representative model farm systems. Combinable farms receiving manure have the same land use as the combinable farms without manure

	DAIRY	LFA - Grazing	Lowland - Grazing	Mixed	Mixed Combinable	Winter Combinable	Roots & Combinable	Indoor Pig	Outdoor Pig	Poultry	Horticulture
Permanent Pasture	71	62	75	74	-	-	15	-	-	-	3
Rotational Grassland	24	5	16	22	-	-	-	-	18	-	-
Rough Grazing	6	79	4	5	5	5	2	-	3	-	-
Winter Wheat	2	-	-	15	102	102	65	-	24	-	-
Winter Barley	-	-	4	10	21	21	9	-	6	-	-
Spring Barley	3	-	1	8	23	-	8	-	6	-	-
Maize	6	-	1	5	-	-	-	-	-	-	-
Sugar Beet	-	-	-	-	-	-	25	-	-	-	-
OSR	-	-	-	8	31	31	-	-	-	-	-
Potatoes	-	-	-	-	-	-	18	-	-	-	-
Fodder Beet	2	-	-	2	-	-	-	-	-	-	-
Other Crops	-	-	-	6	15	-	28	-	-	-	-
Vegetables	-	-	-	-	-	-	10	-	-	-	8
Horticulture	-	-	-	-	-	-	-	-	-	-	7
Total	114	146	101	154	196	159	180	0	57	0	18

Table 5 Summary of the cattle and sheep numbers on each of the representative model farm systems

	DAIRY	LFA - Grazing	Lowland - Grazing	Mixed	Mixed	Combinable	Winter Combinable	Roots & Combinable	Indoor Pig	Outdoor Pig	Poultry	Horticulture
Dairy Cows and Heifers	110	-	-	31	-	-	-	-	-	-	-	-
Dairy Heifers in calf > 2 years	14	-	-	-	-	-	-	-	-	-	-	-
Dairy Heifers in calf < 2 years	14	-	-	-	-	-	-	-	-	-	-	-
Beef Cows and Heifers	-	22	27	21	-	-	-	-	-	-	-	-
Beef Heifers in calf > 2 years	-	3	2	3	-	-	-	-	-	-	-	-
Beef Heifers in calf < 2 years	-	1	1	2	-	-	-	-	-	-	-	-
Bulls	1	1	1	1	-	-	-	-	-	-	-	-
Other Cattle > 2 years	-	11	14	5	-	-	-	-	-	-	-	-
Other Cattle 1 - 2 years	31	14	37	53	-	-	-	-	-	-	-	-
Other Cattle < 1 Year	45	20	39	40	-	-	-	-	-	-	-	-
Total Cattle	215	72	121	156	-	-	-	-	-	-	-	-
Sheep	50	358	184	190	-	-	-	-	-	-	-	-
Lambs	54	339	170	203	-	-	-	-	-	-	-	-
Total Sheep	104	697	354	393	-	-	-	-	-	-	-	-

Table 6 Summary of the pig and poultry numbers on each of the representative model farm systems

	DAIRY	LFA - Grazing	Lowland - Grazing	Mixed	Mixed	Combinable	Winter Combinable	Roots & Combinable	Indoor Pig	Outdoor Pig	Poultry	Horticulture
Sows in Pig and Other Sows	-	-	-	18	-	-	-	-	159	294	-	-
Gilts in Pig and Barren Sows	-	-	-	2	-	-	-	-	71	62	-	-
Gilts Not Yet in Pig	-	-	-	9	-	-	-	-	133	78	-	-
Boars	-	-	-	2	-	-	-	-	6	6	-	-
Other Pigs > 110 kg	-	-	-	4	-	-	-	-	32	-	-	-
Other Pigs 80 - 110 kg	-	-	-	65	-	-	-	-	247	-	-	-
Other Pigs 50 - 80 kg	-	-	-	92	-	-	-	-	621	-	-	-
Other Pigs 20 - 50 kg	-	-	-	102	-	-	-	-	983	-	-	-
Other Pigs < 20 kg	-	-	-	106	-	-	-	-	1272	-	-	-
Total Pigs	-	-	-	400	-	-	-	-	3524	440	-	-
Layers	-	-	-	252	-	-	-	-	-	-	14703	-
Pullet	-	-	-	60	-	-	-	-	-	-	4191	-
Broilers	-	-	-	928	-	-	-	-	-	-	55772	-
Turkeys	-	-	-	642	-	-	-	-	-	-	1379	-
Breeding Birds	-	-	-	358	-	-	-	-	-	-	2602	-
Other Poultry	-	-	-	365	-	-	-	-	-	-	2704	-
Total Poultry	-	-	-	2605	-	-	-	-	-	-	81351	-

3.2. Fertiliser Practice

The quantity of nitrate and phosphate fertiliser used on each land use type on the model farms was taken from the overall use figure reported by the British Survey of Fertiliser Practice (BFSP; 2004). Application rates were not initially adjusted to account for livestock manures, as this would be taken care of under the prior implementation of the mitigation methods. The type and timing of fertiliser applications were taken from a detailed analysis of BSFP returns for 2003 conducted in support of Defra project NT2605 (Chadwick et al., 2005).

3.3. Livestock Calendar

The proportion of time animals spent in housing, gathering yards, milking parlour or at grazing were estimated by month for each livestock type based on data in Hellesten et al. (2007), Webb et al. (2001) and the Defra Farm Practice Survey (2001). The livestock activity data for each farm type were broadly consistent with the default assumptions in the National Ammonia Emissions inventory and the NARSES modelling system (Webb and Misselbrook, 2004). When grazing, animals were located on either the improved grassland or rough grazing. The grazing livestock calendar took account of the grass-cutting regime.

3.4. Manure Management

The quantity and nutrient content of excreta produced by each animal type was calculated according to Cottrill and Smith (2009). The proportion of excreta that was managed as slurry or farmyard manure was defined based on animal type and national survey statistics on animal activity. Estimates were made of the volume of dirty water generated on the hard-standings, and the dilution of slurry in open stores. The timing and location of manure spreading to land was based on Smith et al. (2000; 2001a; 2001b). The model farm descriptions provided an explicit calendar of the location and amount of each type of animal manure spread to each crop type. The method of manure spreading and delay to incorporation (if applicable) were also provided in the farm descriptions.

4. Baseline Pollutant Losses

Baseline pollutant losses do not fully represent the impact of present day standard agricultural practices that will include some method implementation, such as adopting reduced cultivation systems where the Defra Farm Practice Survey estimates that heavy discs or tines are used on 20 to 30% of arable land on combinable crop farms.

Baseline pollutant losses for the representative model farm systems were calculated using a range of computer models used in policy support at farm and national scale. The only requirement was that the losses could be explicitly disaggregated according to the coordinate system described in Section 2.1 (e.g. between source areas, source types and delivery pathways). The models were applied to detailed field scale descriptions of activities for each model farm system.

The gaseous emissions calculations used standard methodologies that were not sensitive to soil type or climate. Therefore, a single set of losses was calculated for each model farm system. The farm losses were re-expressed as export coefficients: per unit of nitrogen applied for ammonia and nitrous oxide; and per m³ of undiluted excreta for methane.

Diffuse agricultural emissions of nitrate, sediment and phosphorus to water are sensitive to local environment factors, including soil type and rainfall. In order to develop loss estimates for the representative farm systems that would scale with agricultural census data to give unbiased national losses, we applied the source models to each and every soil series and average climate statistic that occurred in the 1km² cells within each of the 10 by 10 km² grid cells across England and Wales. The outputs from these detailed calculations were then used to calculate area-weighted average pollutant losses for each of the soil and climate zones (see Section 2.2).

Pollutant losses were calculated for each representative farm system within each of the defined soil and climate zones. As for the gaseous emissions, the losses were then re-expressed as export coefficients: per unit of nitrogen / phosphorus in fertiliser or livestock excreta or per unit area of soil.

Losses of pesticides are also sensitive to local environment factors. However, rather than run the models for each soil type within each 10 by 10 km² grid cells across England and Wales, average drainage and sediment losses for each soil and climate zone were used to run the pesticide model framework once for each climate and soil zone.

Where necessary, pollutant losses were calculated explicitly for each crop and livestock type present on the model farms. These results were then appropriately weighted to provide a single loss coefficient for the generic types of land use (arable, improved grassland and rough grazing) and livestock type (dairy, beef, sheep, pig and poultry) on each farm. This simplification of farm practices made it easier to characterise the targeting of mitigation methods.

4.1. Methane & Nitrous Oxide

Methane is produced as a by-product of enteric fermentation. The quantity of methane released depends on the type of digestive tract, age and weight of the animal, and the quality and quantity of feed consumed. Methane is also emitted by the anaerobic decomposition of animal manures. Emission is greatest in association with liquid storage of manure, and least when manure is deposited directly on pasture. Hence, the system of manure management affects emissions factors. Methane emissions were therefore calculated according to the IPCC (2006) methodology, using default coefficients derived for Western Europe (see also Baggott et al., 2006) with national data on manure management. For dairy cows, calculations were used that took account of the productivity (litres of milk produced), live weight and fat content of the milk. Emissions were calculated as a function of the volatilisable solids in excreta.

The direct and indirect emissions of nitrous oxide from fertiliser, excreta and managed manures were also calculated according to the IPCC methodology (IPCC, 2006; Baggott et al., 2006). This methodology assigns emission factors based on productivity, fertiliser usage and manure management that were defined by the representative model farm descriptions. The IPCC methodology for estimating N₂O losses assumes that 20% of the total nitrogen emitted by livestock volatilises immediately as NO_x and NH₃ and therefore does not contribute to N₂O emissions from storage (Baggott et al., 2006). Our calculations differed slightly in that we explicitly calculated the emissions of ammonia that occurred at each stage (housing, storage and spreading) using the NARSES and MANNER models (Webb and Misselbrook, 2004; Chambers et al., 1999). Hence there are some small differences expected in the emission calculations compared to the default IPCC inventory. Further, the manure management practiced on the model farms was not always directly comparable to the national statistical data used in the spreadsheet inventory maintained by North Wyke Research.

The emissions to air were calculated separately for fertiliser, excreta, managed manures, and leached nitrate and crop residues. Methane emissions were separated between enteric and waste management. The apportionment for nitrous oxide accounted for:

- Crop residues (arable and grass);
- Direct emissions from applied fertiliser (arable and grass);
- Indirect emission from leached fertiliser (arable and grass);
- Indirect atmospheric deposition of ammonia (arable and grass);
- Emissions from animal housing and waste storage (steading);
- Emissions from spreading of managed manure (arable and grass);
- Emissions from direct deposition at grazing (grass and rough grazing);
- Emissions from indirect deposition of ammonia (arable and grass);
- Indirect emission from leached manure nitrogen (arable and grass).

And for methane the apportionment was:

- Enteric (steading, arable, grass and rough grazing);
- Emissions from animal housing and waste storage (steading);
- Emissions from direct deposition at grazing (grass and rough grazing);

4.2. Ammonia

Ammonia emissions from nitrogen fertiliser were calculated based on the NT26AE model and the associated database of fertiliser use by type (Chadwick et al., 2005), derived from the British Survey of Fertiliser Practice (2004). A mean overall emission factor of 3.8% was calculated for fertiliser applied to arable land, and 2.3% for fertiliser applied to grassland. These average factors were calculated from the range of fertiliser types applied (including urea) and held constant for all farm types. The total emission from applied fertiliser was 35.3 kt $\text{NH}_3\text{-N}$. It was noted that this national emission was higher than calculated by the National Emissions Inventory. This was attributed to differences that arose by two methods of calculation: a) the product of crop areas and over-all application rates; b) the use of reported tonnage of nitrogen applied.

Ammonia emissions in housing and during manure storage and from excreta at grazing were calculated using the NARSES model (Webb and Misselbrook, 2004) and by using default assumptions for volatilisation from the steading in the recently derived estimates of excreta nitrogen production (Cottrill and Smith, 2009). Emissions at spreading were calculated using the MANNER model (Chambers et al., 1999), taking account of the method and delay to incorporation specified for each manure type in the representative farm system descriptions.

Note that ammonia emissions have been reported as a nitrogen equivalent ($\text{NH}_3\text{-N}$) in the results tables, and should be multiplied by a factor of 1.22 to give the loss as a mass of the ammonia (NH_3) gas.

The apportionment for ammonia accounted for:

- Direct emissions from applied fertiliser (arable and grass);
- Emissions from animal housing and waste storage (steading);
- Emissions from spreading of managed manure (arable and grass);
- Emissions from direct deposition at grazing (grass and rough grazing);

4.3. Sediment & Phosphorus

The diffuse sediment and phosphorus load from agricultural land was calculated using the PSYCHIC model (Davison et al., 2008; Stromqvist et al., 2008; Collins et al., 2007). This is a process based, monthly time-stepping, model with explicit representation of surface and drain flow hydrological pathways, particulate and solute mobilisation, and incidental losses associated with fertiliser and manure spreading. The model has previously been integrated with the soils, climate and agricultural census data held in the MAGPIE decision support system (Lord and Anthony, 2000) to calculate total phosphorus losses from all agricultural land, including rough grazing and

runoff from hard-standings. The model calculations took account of landscape retention, and are the best available estimate of net delivery to lakes and rivers. The model output has been used previously to support phosphorus and sediment gap analyses for rivers and lakes in England (Anthony et al., 2008; Anthony and Lyons, 2006; Anthony and Collins, 2007). Its application therefore ensured some consistency across a number of projects used to support government policy development.

The PSYCHIC model does not calculate explicit losses from the non-field areas, which was required for this work. Thus estimates were made for the proportion of excreta at grazing that would be directly deposited in water courses whilst the animals were paddling in unfenced off streams, the amount of excreta deposited whilst the animals travelled between the farmstead and the fields (and the amount of excreta deposited directly in watercourses if fording of streams was required), and the amount of excreta deposited whilst they were on hardstandings during the winter or waiting to be milked. These figures were based on data collated under the ongoing Defra project WQ0111. Excreta directly to water was left 'as is', whilst excreta on tracks and hardstandings was modified to account for the likelihood of being washed off in rainfall. It was also necessary to account for the phosphorus leached from field-based manure heaps.

The apportionment for sediment was simply:

- Soil (arable, grass and rough grazing);

Whilst for phosphorus the apportionment was:

- Soil (arable, grass and rough grazing);
- Incidental emissions from applied fertiliser (arable and grass);
- Incidental emissions from excreta at grazing (rough grazing and grass);
- Incidental emissions from spreading of managed manure (arable and grass);
- Direct emission by grazing cattle with access to water;
- Direct emission by fording, and runoff from cattle tracks;
- Runoff from yards and hard standings;
- Leaching from solid manure heaps.

4.4. Nitrate

Nitrate losses were calculated based upon the NEAP-N model (Lord and Anthony, 2000). This model was suited to the national scale based methodology, but although it is sensitive to crop type and stocking density, it does not provide the detailed apportionment required for this work. Therefore the lumped base coefficients in the NEAP-N model were disaggregated according to the results of a selection of models which are sensitive to cropping history, fertiliser and manure nitrogen inputs and crop off-take, stocking density, and soil hydrology. N-CYCLE (Scholefield et al., 1991) was used to disaggregate the grassland and livestock coefficients; NITCAT (Lord, 1992) for cropping coefficients; MANNER (Chambers et al., 1999) for the

contribution from applied manures and EDEN (Gooday et al., 2008) for assessing the proportion of the losses by the different pathways. To ensure a common hydrological basis between the water based pollutants, the combined N model was linked to the PSYCHIC model used for sediment and phosphorus losses so that it could use the output of the PSYCHIC water balance model component.

Losses of nitrate from non-field areas were calculated in an identical way to those for phosphorus.

All of the nitrate models mentioned have previously been used to support the evaluation of Defra nitrates policy and/or the designation of the Nitrate Vulnerable Zones.

The apportionment recognised for nitrate was:

- Medium term soil nitrogen (arable, grass and rough grazing);
- Incidental emissions from applied fertiliser (arable and grass);
- Incidental emissions from spreading of managed manure (arable and grass);
- Incidental emissions from excreta at grazing (rough grazing and grass);
- Medium term emissions due to applied fertiliser;
- Medium term emissions due to spreading of manage manure (arable and grass);
- Medium term emissions due to excreta at grazing (rough grazing and grass);
- Long term emissions from prior spreading of managed manure (arable and grass);
- Long term emissions from prior excreta at grazing (rough grazing and grass);
- Direct emission by grazing cattle with access to water;
- Direct emission by fording, and runoff from cattle tracks;
- Runoff from yards and hard standings;
- Leaching from solid manure heaps.

4.5. Pesticides

Pesticide losses were calculated using a combination of several industry standard models and approaches, as no one model existed that captured each of the coordinates considered in this framework.

To enable the calculation of pesticide losses, standardised usage amounts of fungicide, herbicide, insecticide, molluscicide and growth regulators were created for each of the crop types found on the model farms based on published statistics (e.g. Garthwaite et al., 2005; 2006).

Losses of pesticides in leaching were based upon the Macro tool (Jarvis, 1994). The tool was applied to a theoretical pesticide, with a range of sorption

coefficients and degradation rates, for representative soils and with a long-term weather dataset, in order to develop a set of outputs that summarised the detailed model calculations. This produced a set of look-up tables for the three soil types considered, that gave estimated average pesticide concentrations for a standard application of 1,000 g ha⁻¹ of active ingredient for different climate zones. These concentrations could be integrated with average annual effective rainfall amounts to provide the percentage loss for a unit application of each listed pesticide. An overall average percentage loss for each crop type was then calculated by weighting the results of the individual average proportions of the full label rate and the total area of crop treated. This allowed us to take account of the different properties affecting the leaching potential (sorption coefficients and degradation rates) of the different pesticides.

Losses of pesticides in runoff and drain flow were based on a version of the SWAT model (Brown and Hollis, 1996) which had been modified to look at all drainage events in a season (rather than just the first event after application). The model was applied to a theoretical pesticide with a range of sorption coefficients and degradation rates for a range of soils and climate zones, as per the MACRO tool modelling, so that percentage full dose units lost could be derived. As per the leaching losses, an overall average percentage loss in runoff and drain flow for each crop type was calculated by weighting the results of the individual average pesticide proportions of the full label rate and the total area of crop treated.

Losses of pesticide attached to soil particles were derived from equations linked to the average sediment losses calculated for each land use within the climate and soil zones. As per the leaching and runoff losses, this was run for all the different pesticides and the results weighted according to the individual pesticide full label rates and total areas treated.

Losses of pesticides in spray drift to ditches were quantified by application of the Ganzelmeir et al. (1995) equations to standard scenarios for ditches (FOCUS, 2002). All drained fields were assumed to have a ditch run alongside one field edge. For non-drained fields, the probability of there being a water course on one side of the field was derived for each climate zone based on the average stream density and distance to water course within each climate zone.

Losses of pesticide on the steading were calculated in proportion to the number of spray rounds completed - this represents the number of occasions on which there is opportunity for spillage and runoff. Research in the UK and Europe has shown that 20 to 90% of the total pesticide load leaving a surface water catchment can originate from handling operations on the steading (Rose et al., 2004; Mason et al., 1999; Jaeken and Debaer, 2005). The loss from the steading for each farm type was therefore set to be 50% of the total for the 600-700 mm rainfall climate zone on the most impermeable of the soil types considered.

The apportionment recognised for pesticides was:

- Incidental losses from pesticide application (arable, grass and rough grazing);

- Direct losses to water through spray drift (arable, grass and rough grazing);
- Runoff from hard standings.

5. Pollution Mitigation Methods

Potential pollutant mitigation methods were identified from the 'User Guide' of mitigation methods (Newell-Price et al., 2009). This project identified 96 potential methods. Mitigation methods were excluded from this study if they: a) resulted in a direct change in farm system; b) had zero net effect at national scale; c) were relevant only to the control of pathogens; or d) are presently illegal. A total of 76 mitigation methods were selected for inclusion in this study, although three of these were subdivided to allow for improved targeting using the coordinate system. A description of each original method, the expected method of action, its practicability and likely level of uptake is given in Newell-Price et al. (2009). The method numbering corresponds to the system used in the 'User Guide', with the three subdivided methods having a 0 or 1 appended to the original 2-digit number.

5.1. Method Applicability

The mitigation methods were scoped for applicability by identifying potential environmental and system constraints. For example, cover crops were limited to the area of spring-sown cereals, and contour cultivation was limited to areas with a slope less than seven degrees.

5.2. Method Cost

The cost of agricultural diffuse pollution control was calculated as the sum of the amortised annual farm costs of the individual mitigation methods selected by an optimisation scenario. Costs were amortised over 5 to 20 years dependent on the expected lifetime of the capital investment. The costs were calculated net of any prior method implementation. The costs represented the cost to the farm sector only, and excluded any costs to government in administering any scheme that supported or enforced method implementation.

The implementation of a pollutant mitigation method may alter farm finances by changing the variable costs and gross margin of a crop or stock enterprise; by changing the fixed costs or overheads associated with labour and machinery; or by requiring a capital investment (Withers et al., 2003). Mitigation methods may give rise to costs in more than one category. The appropriate farm costs for each of the mitigation methods considered by this study were calculated from a range of sources. Extensive use was made of cost estimates reported by Cuttle et al. (2006), Ryan (2003) and Anthony et al. (2008). These were supported by occasional unit cost data taken from Nix (2009) and CCW (2005), and from cost assessments made in studies of specific mitigation methods such as Carty et al. (2008) and Theobald et al. (2004).

Mitigation method costs in the literature are normally reported as a net cost for a specific farm system. To enable scaling of the costs and application to a range of farm types and sizes, the available cost data were re-expressed as unit costs in one of three ways:

- Excreta Unit Cost

The annual mitigation method cost was expressed per cubic metre of all livestock excreta produced on a farm. The assumption was that the cost represents farm inputs that are directly in proportion to the numbers of animals, and hence the total quantity of excreta produced on the farm. For example, dietary supplements are in proportion to the animal diet and therefore excreta production; and the roofing of concrete yards will be in proportion to the yard size that is also in proportion to animal numbers or excreta production. In effect, excreta production is used as a form of livestock unit.

- Manure Unit Cost

The annual mitigation method cost was expressed per cubic metre of managed slurry or farm yard manure on a farm. The assumption was that the cost represents additional handling and storage costs that are in proportion to the quantity of manure. For example, restrictions on the placement of manure next to watercourses require additional planning time; and restrictions on timing of manure application may require additional storage facilities.

- Area Unit Cost

The annual mitigation method cost was expressed per hectare of arable, grass or rough grazing on the farm. The assumption was that the cost represents income foregone or labour that is in proportion to the land area. For example, riparian buffer zones require land to be taken out of production; and the cultivation of compacted soils requires an extra tillage operation.

Table 7 summarises the derived unit costs for each of the mitigation methods used in this study. The costs of method implementation for a farm type are calculated as the product of the unit costs and the relevant land area or quantity of excreta and managed manure. Where a mitigation method had limited applicability, the unit cost has been expressed per unit of land or manure to which the method is applied. Therefore it was necessary when scaling to a whole farm to take account of the proportion of land to which a method was applicable. For example, the sowing of a cover crop is limited to spring sown arable crops.

The unit costs were expressed as an amortised annual cost, using standard assumptions for the replacement period of any capital items such as fencing, and an annual discounting rate of 7%. These costs represent the total cost of the mitigation method, and do not allow for any support mechanism. The mitigation method costs are generally comparable to those used in previous cost effect studies (Cuttle et al., 2007; Dwyer et al., 2002). Comparison of typical whole farm costs reported by Cuttle et al. (2007) with those from this project will reveal differences that are largely due to changes in the definition of a typical farm (such as total land area or stock numbers) rather than changes in the unit costs. These method costs are sensitive to the detail and scale of an individual farm enterprise. The net costs of many methods are also very sensitive to short-term changes in the cost of inputs, notably fuel and fertiliser, and the market value of produce. Caution is therefore advised in applying the cost estimates to any individual enterprise.

Table 7 Unit cost for method implementation, relevant to target areas listed

ID	Method Name	Cost Per Unit...	Cost (£)	Target Area	Target Animal	Target Manure
4	Establish cover crops in the autumn	Area	60	Arable	-	-
5	Early harvesting and establishment of crops in the autumn	Area	650	Arable	-	-
6	Cultivate land for crops in spring rather than autumn	Area	100	Arable	-	-
7	Adopt reduced cultivation systems	Area	-40	Arable	-	-
8	Cultivate compacted tillage soils	Area	4	Arable	-	-
9	Cultivate and drill across the slope	Area	10	Arable	-	-
10	Leave autumn seedbeds rough	Area	40	Arable	-	-
11	Manage over-winter tramlines	Area	25	Arable	-	-
13	Establish in-field grass buffer strips	Area	5	Arable	-	-
14	Loosen compacted soil layers in grassland fields	Area	10	Grass	-	-
15	Establish riparian buffer strips	Area	10	Arable	-	-
16	Allow field drainage systems to deteriorate	Area	10	Grass	-	-
16	Allow field drainage systems to deteriorate	Area	50	Arable	-	-
19	Make use of improved genetic resources in livestock	Volume	-2	-	Dairy Beef Sheep	Total Excreta
20	Use plants with improved nitrogen use efficiency	Area	-10	Grass	-	-
20	Use plants with improved nitrogen use efficiency	Area	-20	Arable	-	-
21	Fertiliser spreader calibration	Area	1	Arable Grass	-	-
22	Use a fertiliser recommendation system	Area	-5	Grass	-	-
22	Use a fertiliser recommendation system	Area	-10	Arable	-	-
23	Integrate fertiliser and manure nutrient supply	Volume	-35	-	All	Litter
23	Integrate fertiliser and manure nutrient supply	Volume	-5	-	All	Slurry
23	Integrate fertiliser and manure nutrient supply	Volume	-10	-	All	FYM
25	Do not apply fertiliser to high-risk areas	Area	0.5	Grass	-	-
25	Do not apply fertiliser to high-risk areas	Area	5	Arable	-	-
26	Avoid spreading fertiliser to fields at high-risk times	Area	0.5	Grass	-	-
26	Avoid spreading fertiliser to fields at high-risk times	Area	5	Arable	-	-
27	Fertiliser placement	Area	2	Arable	-	-
290	Replace urea fertiliser to grassland with another form (e.g. ammonium nitrate)	FertiliserN	-0.03	Grass	-	-
300	Incorporate a urease inhibitor into urea fertilisers for grassland	Area	0	Grass	-	-

ID	Method Name	Cost Per Unit...	Cost (£)	Target Area	Target Animal	Target Manure
291	Replace urea fertiliser to arable land with ammonium nitrate)	FertiliserN	-0.03	Arable	-	-
301	Incorporate a urease inhibitor into urea fertilisers for arable land	Area	0	Arable	-	-
31	Use clover in place of grass	Area	-60	Grass	-	-
32	Do not apply P fertilisers to high P index soils	Area	-5	Arable Grass	-	-
331	Reduce dietary N and P intakes: Dairy	Volume	1.8	-	Dairy	Total Excreta
332	Reduce dietary N and P intakes: Pigs and Poultry	Volume	1.5	-	Pigs	Total Excreta
332	Reduce dietary N and P intakes: Pigs and Poultry	Volume	0.3	-	Poultry	Total Excreta
34	Adopt phase feeding of livestock	Volume	0.75	-	Dairy Pigs	Total Excreta
35	Reduce the length of the grazing day/grazing season	Volume	1.8	-	Dairy	Total Excreta
35	Reduce the length of the grazing day/grazing season	Volume	0.7	-	Beef	Total Excreta
36	Extend the grazing season for cattle	Volume	0.2	-	Beef	Total Excreta
36	Extend the grazing season for cattle	Volume	0.6	-	Dairy	Total Excreta
37	Reduce field stocking rates when soils are wet	Volume	0.7	-	Beef	Total Excreta
37	Reduce field stocking rates when soils are wet	Volume	1.8	-	Dairy	Total Excreta
38	Move feeders at regular intervals	Area	10	Grass	-	-
38	Move feeders at regular intervals	Area	30	Grass	-	-
39	Construct troughs with concrete base	Area	5	Grass	-	-
41	Improved feed characterisation	Volume	0	-	-	-
44	Increase scraping frequency in dairy cow cubicle housing	Volume	2	-	Dairy	Total Excreta
45	Additional targeted bedding for straw-bedded cattle housing	Volume	5	-	Beef	Total Excreta
46	Washing down of dairy cow collecting yards	Volume	0.5	-	Dairy	Total Excreta
48	Frequent removal of slurry from beneath-slat storage in pig housing	Volume	2	-	Pigs	Total Excreta
49	Improved slatted-floor design for pig buildings	Volume	2	-	Pigs	Total Excreta
50	Install air-scrubbers or biotrickling filters to mechanically ventilated pig housing	Volume	5	-	Pigs	Total Excreta
51	Convert layer hen housing from deep-pit to belt manure removal	Volume	30	-	Poultry	Litter
52	Frequent manure removal from layer hen housing with manure belts	Volume	0.1	-	Poultry	Total Excreta
53	In-house poultry manure drying	Volume	2.8	-	Poultry	Total Excreta
54	Increase the capacity of farm manure (slurry) stores	Volume	0.85	-	Dairy Pigs	Total Excreta
55	Adopt batch storage of slurry	Volume	4	-	Dairy Pigs	Slurry
56	Install covers to slurry stores	Volume	1	-	Dairy Pigs	Slurry

ID	Method Name	Cost Per Unit...	Cost (£)	Target Area	Target Animal	Target Manure
57	Allow cattle slurry stores to develop a natural crust	Volume	0.15	-	Dairy	Slurry
59	Minimise the volume of dirty water produced	Volume	1	-	All	Total Excreta
60	Adopt batch storage of solid manure	Volume	0.25	-	All	FYM
61	Compost solid manure	Volume	2.5	-	All	FYM
62	Store solid manure heaps away from watercourses/drains	Volume	0.1	-	All	FYM
63	Store solid manure heaps on concrete and collect effluent	Volume	0.5	-	All	FYM
64	Cover manure stores with polythene sheeting	Volume	0.55	-	All	FYM
65	Liquid/solid manure separation	Volume	1	-	Dairy Pigs	FYM Slurry
66	Manure additives (e.g. Alum)	Volume	0.7	-	Poultry	Total Excreta
69	Manure Spreader Calibration	Area	2	Arable Grass	-	-
70	Do not apply manure to high-risk areas	Volume	0.1	-	All	FYM Slurry Litter
71	Do not spread slurry at high-risk times	Volume	0.1	-	Dairy Beef Pigs Poultry	Slurry Litter
72	Slurry band spreading application techniques	Volume	1.5	-	Dairy Beef Pigs	Slurry
73	Use slurry injection techniques	Volume	2	Grass	Dairy Beef Pigs	Slurry
74	Do not spread FYM to fields at high-risk times	Volume	0.1	-	All	FYM
75	Incorporate manure into the soil	Volume	1	Arable	All	FYM Slurry Litter
78	Fence off rivers and streams from livestock	Area	10	Grass	-	-
79	Construct bridges for livestock crossing rivers/streams	Area	10	Grass	-	-
80	Re-site gateways away from high-risk areas	Area	2	Arable Grass	-	-
81	Farm track management	Area	2.5	Arable Grass	-	-
82	Establish new hedges	Area	25	Arable Grass	-	-
83	Establish and maintain artificial wetlands - steading runoff	Volume	0.6	-	Dairy Beef	Total Excreta
84	Irrigate crops to achieve maximum yield	Area	300	Arable	-	-
85	Establish tree shelter belts around livestock housing	Volume	0.2	-	Poultry	Total Excreta
90	Calibration of sprayer	Area	2	Arable Grass	-	-
91	Fill/Mix/Clean sprayer in field	Area	4	Arable	-	-
92	Avoid PPP application at high risk timings	Area	25	Arable	-	-
94	Drift reduction methods	Area	2	Arable	-	-
95	PPP substitution	Area	2	Arable	-	-
96	Construct bunded impermeable PPP filling/mixing/cleaning area	Area	4	Arable	-	-
97	Treatment of PPP washings through either; disposal, activated carbon or biobeds	Area	4	Arable	-	-

5.3. Method Effectiveness

The effectiveness of the mitigation methods were characterised as a percentage reduction against the pollutant loss from a set of loss coordinates.

The effectiveness values were based on a number of existing literature reviews and expert judgement (Anthony et al., 2008; Cuttle et al., 2008; Webb and Misselbrook, 2004; Moorby et al., 2007). The method effectiveness values are assumed to incorporate any efficiencies of implementation.

Table 8 Average percentage effectiveness classes and uncertainty range for mitigation methods.

Class	Average	Uncertainty Range	Pollution Reduction
A	-	-	None
B	2	0 to 10	Very Low
C	10	2 to 25	Low
D	25	10 to 50	Moderate
E	50	25 to 80	High
F	80	50 to 95	Very High
G	100	100	Total

It was evident from the literature that although detailed information may be available on the percentage impact of an individual method in some publications, this is not generally the case. Also, there is a large variation in the reported values of mitigation method effect, and in some cases there is no quantitative data at all. Therefore, mitigation method effect was summarised on an indicator scale that gives some guidance on the potential range of impacts (Table 8). Note that the average values in Table 8 are lower than the central values of the ranges – they thus represent a cautious assessment of the average estimate. In the use of these ranges for sensitivity analysis, the mean result is thus slightly higher than that achieved using the average impact. This scaling of uncertainty is common in the assessment of environmental processes.

Although costs were shown in Table 7 for all methods, a table of method effectiveness is too cumbersome to fit into this report due to number of impacts of each method resulting from the coordinate targeting system. A small sample of method effectiveness data is shown in Table 9.

Table 9 Targeting and impact for a small selection of mitigation methods

ID	Method Name	Pollutant	Source	Area	Pathway	Type	Timescale	Form	Impact
4	Establish cover crops in the autumn	Phosphorus	Soil	Arable	Runoff Preferential	Soil	Short	Particulate	D
4	Establish cover crops in the autumn	Sediment	Soil	Arable	Runoff Preferential	Soil	Short	Particulate	D
4	Establish cover crops in the autumn	Nitrate	Soil	Arable	Preferential Leaching	Soil	Medium	Dissolved	E
4	Establish cover crops in the autumn	Nitrate	Chemical	Arable	Preferential Leaching	Fertiliser	Medium	Dissolved	E
4	Establish cover crops in the autumn	Nitrate	AllAnimal	Arable	Preferential Leaching	FYM Slurry Litter	Medium	Dissolved	E
4	Establish cover crops in the autumn	Pesticides	Chemical	Arable	Runoff Preferential	PPPs	Short	Particulate	C
36	Extend the grazing season for cattle	Methane	Dairy Beef	Grass	Gaseous	Voided	Short	Gas	-D
36	Extend the grazing season for cattle	Methane	Dairy Beef	Storage	Gaseous	FYM Slurry	Short	Gas	D
36	Extend the grazing season for cattle	Nitrous_Oxide	Dairy Beef	Grass	Gaseous	Voided	Short Long	Gas	-C
36	Extend the grazing season for cattle	Nitrous_Oxide	Dairy Beef	Storage	Gaseous	FYM Slurry	Short Long	Gas	D
36	Extend the grazing season for cattle	Phosphorus	Dairy Beef	AllNonField	Runoff	Voided	Short	Dissolved	-B
36	Extend the grazing season for cattle	Phosphorus	Soil	Grass	Runoff Preferential	Soil	Short	Particulate	-B
36	Extend the grazing season for cattle	Phosphorus	Dairy Beef	Grass	Runoff Preferential	Voided	Short	Dissolved	-B
36	Extend the grazing season for cattle	Sediment	Soil	Grass	Runoff	Soil	Short	Particulate	-B
36	Extend the grazing season for cattle	Ammonia	Dairy	Grass	Gaseous	Voided	Short	Gas	-D
36	Extend the grazing season for cattle	Ammonia	Dairy	Housing	Gaseous	Voided	Short	Gas	D
36	Extend the grazing season for cattle	Ammonia	Dairy	Storage	Gaseous	Slurry FYM	Short	Gas	D
36	Extend the grazing season for cattle	Ammonia	Dairy	AllField	Gaseous	Slurry FYM	Short	Gas	D
36	Extend the grazing season for cattle	Ammonia	Beef	Grass	Gaseous	Voided	Short	Gas	-D
36	Extend the grazing season for cattle	Ammonia	Beef	Housing Yards	Gaseous	Voided	Short	Gas	D
36	Extend the grazing season for cattle	Ammonia	Beef	Storage	Gaseous	Slurry FYM	Short	Gas	D
36	Extend the grazing season for cattle	Ammonia	Beef	AllField	Gaseous	Slurry FYM	Short	Gas	D
36	Extend the grazing season for cattle	Nitrate	Dairy Beef	AllNonField	Runoff	Voided	Short	Dissolved	-B
36	Extend the grazing season for cattle	Nitrate	Dairy Beef	Grass	Runoff Preferential Leaching	Voided	Short	Dissolved	-B
57	Allow cattle slurry stores to develop a crust	Methane	Dairy Beef	Storage	Gaseous	Slurry	Short	Gas	E
57	Allow cattle slurry stores to develop a crust	Ammonia	Dairy Beef	Arable Grass	Gaseous	Slurry	Short	Gas	-B
57	Allow cattle slurry stores to develop a crust	Ammonia	Dairy Beef	Storage	Gaseous	Slurry	Short	Gas	E
92	Avoid PPP application at high risk timings	Pesticides	Chemical	Arable Grass	Runoff Preferential	PPPs	Short	Dissolved Particulate	C

The literature data and expert interpretation provided estimates of the effectiveness of mitigation methods applied alone. The model framework used in this analysis by necessity calculated the impact of implementing a combination of mitigation methods that might target the same loss coordinates. To account for this, the pollution reduction R due to each mitigation method was first scaled in proportion to the efficiency E of implementation:

$$R = P \cdot E \quad \text{Equation 1}$$

where P is the expected effectiveness under optimal conditions. In this equation and all others, the percentage effectiveness and efficiency values are re-expressed as fractions (- to 1). Note that E was assumed to be 100% for all mitigation methods in this study but the functionality remains in the framework to change this.

If the mitigation methods were applicable to all of the land on a farm, then the net reduction N due to a suite of methods was calculated using a multiplicative model as:

$$N = 1 - \prod_{i=1}^{i=n} (1 - R_i) \quad \text{Equation 2}$$

where R_i is the reduction due to an individual method. In the circumstances that one or more methods were not implemented across the whole farm, we have made an assumption of maximum overlap of method uptake (the product of applicability and implementation):

$$N = \sum_{j=1}^{j=n} A_{1,j} \cdot \left(1 - \prod_{i=1}^{i=j} (1 - R_i) \right) \quad \text{Equation 3}$$

where $A_{1,j}$ is the proportion of the farm area affected by methods 1 to j and N is the net effect of all the methods. This is in effect an area-weighted version of Equation 1. Figure 3 makes this approach explicit.

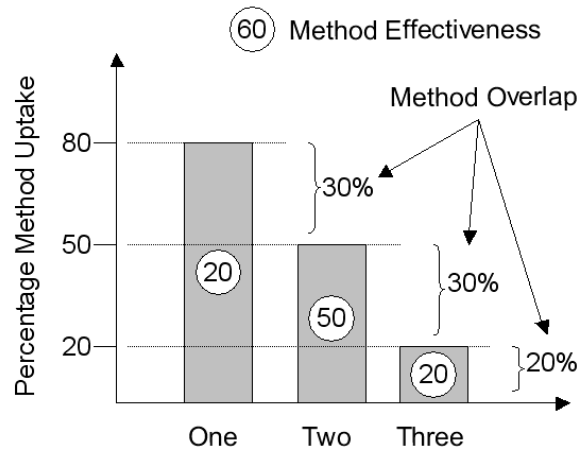


Figure 3 Schematic of the method of calculating the net effectiveness of a suite of mitigation methods, assuming maximum overlap of method implementation.

Three methods are shown on the graph of method implementation or uptake with values of 80%, 50% and 20%. They are ordered by decreasing uptake. The effectiveness values of the individual methods are 20%, 50% and 20%, respectively. The net effect is determined from the 30% of the farm source area impacted by only the first method with an effectiveness of 20%; the 30% of the farm source area impacted by the first and second methods with a combined effectiveness of 60%; and the 20% of the farm source area impacted by all three methods with a combined effectiveness of 68% (Equation 2). The net effect is a weighted sum of these combined effectiveness values, where the weight is the area of overlap. In this case, the combined effectiveness of all three methods (including the area of the farm that is not impacted by any method) is 37.6% (Equation 3).

The method of calculating the net effectiveness of multiple methods assumed that methods are acting on the same potential pollutant source. Therefore, the gain from additional methods decreases rapidly. This is not a perfect model but is thought to be better than the alternative additive model in which the pollutant source is quickly exhausted and the impact of multiple methods over-estimated.

The effectiveness values for mitigation methods were allowed to take negative values. For certain methods, this represents 'pollution swapping', where a reduction in one pollutant is associated with an increase in another. Mitigation methods that reduce losses at one farm location may inadvertently increase losses from elsewhere.

5.4. Prior Implementation

Assessing the potential impact of diffuse pollution mitigation method implementation required an assessment of the extent of prior implementation of each of the methods by landowners in response to existing environment, economic and social drivers. Calculating the impact of prior implementation also allowed an estimate of the true present day pollutant losses.

The evidence base to support this assessment was sparse, although data from the Farm Practices Survey (Defra, 2001 to 2008) was used for some mitigation methods, together with data on recommendations made to farmers under the England Catchment Sensitive Farming Delivery Initiative (ECSFDI; Environment Agency, 2008; Appendix 9), and a small number of questionnaire returns from Environment Scheme officers within the Welsh Assembly Government (Anthony et al., 2008). The final prior implementation estimates were therefore largely derived by expert consultation within ADAS, making use of a small expert group that had previously been involved in the assessment of method implementation for Defra projects WQ0106, ES0205, WT0750CSF and WT0743CSF (Shepherd et al., 2007; Anthony, 2006; Anthony et al., 2008; Anthony et al., 2008).

In order to explicitly recognise the inherent uncertainty, the prior implementation estimates were summarised on an indicator scale that gave some guidance on the potential range of implementation (Table 10). It is important to note that implementation was here interpreted as the percentage of the relevant agricultural land area on which a mitigation method was implemented. For example, the implementation of autumn sown cover crops

was expressed as a percentage of the relevant spring cereal area. The final expert derived prior implementation scores are listed by Table 11. Because of large areas of England and Wales that are within NVZs, and the impact that this has on the prior implementation of certain methods (e.g. using fertiliser recommendation systems and integrating fertiliser and manure nutrient supplies), two sets of values are shown which are felt to represent implementation on those farms within NVZs and those outside them. However, the results in this report are produced using the values for Non-NVZ farms, with the NVZ figures available for guidance in further use of the framework created and to aid discussion of the results.

Table 10 Average percentage implementation classes and associated uncertainty range for mitigation methods.

Class	Average	Uncertainty Range	Implementation Extent
A	-	-	None
B	2	- to 10	Very Low
C	10	2 to 25	Low
D	25	10 to 50	Moderate
E	50	25 to 80	High
F	80	50 to 95	Very High
G	100	100	Standard

Table 11 Estimates of prior implementation for the mitigation methods within and without NVZs.

ID	Method Name	Prior Imp.	
		Non-NVZ	NVZ
4	Establish cover crops in the autumn	B	B
5	Early harvesting and establishment of crops in the autumn	A	A
6	Cultivate land for crops in spring rather than autumn	B	B
7	Adopt reduced cultivation systems	D	D
8	Cultivate compacted tillage soils	C	C
9	Cultivate and drill across the slope	C	C
10	Leave autumn seedbeds rough	C	C
11	Manage over-winter tramlines	B	B
13	Establish in-field grass buffer strips	B	B
14	Loosen compacted soil layers in grassland fields	C	C
15	Establish riparian buffer strips	C	C
16	Allow field drainage systems to deteriorate	B	B
19	Make use of improved genetic resources in livestock	A	A
20	Use plants with improved nitrogen use efficiency	A	A
21	Fertiliser spreader calibration	B	B
22	Use a fertiliser recommendation system	D	F
23	Integrate fertiliser and manure nutrient supply	D	F
25	Do not apply fertiliser to high-risk areas	C	C
26	Avoid spreading fertiliser to fields at high-risk times	A	C
27	Fertiliser placement	C	C
290	Replace urea fertiliser to grassland with another form	A	A
291	Replace urea fertiliser to arable land with another form	A	A

ID	Method Name	Prior Imp.	
		Non-NVZ	NVZ
300	Incorporate a urease inhibitor into urea fertilisers for grassland	A	A
301	Incorporate a urease inhibitor into urea fertilisers for arable land	A	A
31	Use clover in place of grass	A	A
32	Do not apply P fertilisers to high P index soils	C	C
331	Reduce dietary N and P intakes: Dairy	F	F
332	Reduce dietary N and P intakes: Pigs and Poultry	F	F
34	Adopt phase feeding of livestock	F	F
35	Reduce the length of the grazing day/grazing season	B	B
36	Extend the grazing season for cattle	B	B
37	Reduce field stocking rates when soils are wet	C	C
38	Move feeders at regular intervals	C	C
39	Construct troughs with concrete base	B	B
41	Improved feed characterisation	A	A
44	Increase scraping frequency in dairy cow cubicle housing	A	A
45	Additional targeted bedding for straw-bedded cattle housing	A	A
46	Washing down of dairy cow collecting yards	F	F
48	Frequent removal of slurry from beneath-slat storage in pig housing	A	A
49	Improved slatted-floor design for pig buildings	A	A
50	Install air-scrubbers or biotrickling filters to mechanically ventilated pig housing	A	A
51	Convert layer hen housing from deep-pit to belt manure removal	A	A
52	Frequent manure removal from layer hen housing with manure belts	A	A
53	In-house poultry manure drying	C	C
54	Increase the capacity of farm manure (slurry) stores	B	C
55	Adopt batch storage of slurry	A	A
56	Install covers to slurry stores	B	C
57	Allow cattle slurry stores to develop a natural crust	F	F
59	Minimise the volume of dirty water produced	B	C
60	Adopt batch storage of solid manure	B	B
61	Compost solid manure	B	B
62	Store solid manure heaps away from watercourses/drains	D	E
63	Store solid manure heaps on concrete and collect effluent	C	D
64	Cover manure stores with polythene sheeting	A	B
65	Liquid/solid manure separation	B	B
66	Manure additives (e.g. Alum)	A	A
69	Manure Spreader Calibration	A	B
70	Do not apply manure to high-risk areas	D	E
71	Do not spread slurry at high-risk times	A	C
72	Slurry band spreading application techniques	B	B
73	Use slurry injection techniques	B	B
74	Do not spread FYM to fields at high-risk times	A	D
75	Incorporate manure into the soil	C	B
78	Fence off rivers and streams from livestock	D	D
79	Construct bridges for livestock crossing rivers/streams	B	B
80	Re-site gateways away from high-risk areas	A	A
81	Farm track management	A	B
82	Establish new hedges	B	B
83	Establish and maintain artificial wetlands - steading runoff	A	A
84	Irrigate crops to achieve maximum yield	E	E
85	Establish tree shelter belts around livestock housing	A	A

ID	Method Name	Prior Imp.	
		Non-NVZ	NVZ
90	Calibration of sprayer	E	E
91	Fill/Mix/Clean sprayer in field	D	D
92	Avoid PPP application at high risk timings	F	F
94	Drift reduction methods	E	E
95	PPP substitution	C	C
96	Construct bunded impermeable PPP filling/mixing/cleaning area	B	B
97	Treatment of PPP washings through disposal, activated carbon or biobeds	B	B

5.5. Method Competition

Competition represents two or more methods which cannot be active at the same time e.g. extension and reduction of the grazing season. If two active methods are in competition, then the one with the higher priority takes precedence. Where the non-dominant method has a higher implementation (due to greater applicability or higher prior implementation), then the non-dominant method will be applied to the remaining fraction assuming maximum overlap with the dominant method. Competitive methods are assumed to be in groups, with a method allowed to be in only one competitive group.

5.6. Method Dependency

Dependency represents where the implementation of one method is only effective if another method has already been implemented e.g. 'frequent manure removal from layer hen housing with manure belts' is dependent on the method 'convert layer hen housing from deep-pit to belt manure removal' already being in place. If a method is dependent on another method that is only partially implemented, then the implementation of the dependent method cannot be greater than the partial implementation of the method upon which it is dependent. In the framework created, it has been assumed that a dependent method can only be implemented beyond its prior levels if the method upon which it is dependent is also being further implemented.

It is possible to create situations with nested dependency or interlinked dependency and competition. If so, then any partial implementation or limits to maximum implementation are accounted for.

5.7. Method Grouping

Grouping of methods is used to force a suite of methods to be selected as one; thus they can be used to represent the combined effects of an environment scheme, action programme or similar. Dependency of any method within the group is only important for that method, and does not impinge upon the extent of implementation of any other method within the group. If any method within the group is in competition with a method outside the group, then the whole group is in effect in competition with that method, although only the actual competitive method can have its implementation reduced due to prior implementation of the method with which it is competitive (unless its implementation is reduced to zero, in which case the whole group

is inactive). Method grouping is only relevant for optimisation, and only where methods are active (inactive methods within a group are ignored).

6. Mitigation Method Optimisation

The identification of optimal suites of methods that reduced multiple pollutant losses could in principle be found by simulating all possible combinations of mitigation methods, but this is a numerically intensive task that scales exponentially with the number of mitigation methods. For example, in the case of thirty methods, there are more than a billion different method combinations, making it unfeasible to evaluate all the possible solutions in a reasonable amount of time. Another pragmatic approach for selecting a good set of mitigation methods is to construct a cost-curve by iteratively selecting the most cost-effective method. However, the cost-effectiveness is dependent on the methods already implemented and this approach falls short of recognising situations where it may be preferable to select one costly method with a lower cost-effectiveness over a number of smaller methods each with a higher cost-effectiveness. The cost-curve approach was also difficult to apply in this context without deriving a single weighted objective from the multiple pollutants. It was then possible that the optimal combination of methods would be overlooked, as the optimisation process would be pre-emptively constrained.

It was therefore necessary to adopt a more sophisticated approach to identify the optimal method combinations. A large number of local and global optimization techniques are available. Veith (2002) evaluated different optimization techniques for solving combinatorial optimization problems and concluded that tabu search, simulated annealing and genetic algorithms are suitable methods for this kind of problem because they perform a global search and do not require continuously changing input parameters. As genetic algorithms are relatively easy to implement and have already been successfully used for the selection of a best set of mitigation methods in several studies of diffuse pollution control (see, for example, Srivastava et al., 2002; Veith et al., 2003; Gitau et al., 2004) this approach was also applied here. The genetic algorithm model conceptually represents potential solutions to a method selection problem as a chromosome, with the genes on the chromosome representing whether an individual mitigation method is active. A population of chromosomes is maintained and at each iteration of the optimisation process, the chromosomes that are judged to be most fit are preferentially selected to survive into the next generation and reproduce. Reproduction by chromosome cross-over and mutation generates child chromosomes that direct the search into new areas of the search space. Repetition creates a generation of individual solutions that are on average fitter than the previous generation in a process analogous to evolution. For a good introduction to genetic algorithms see Goldberg (1989).

Coello et al. (2007) have reviewed the types of genetic algorithm model applicable to multiple objective optimisations. Multiple objective algorithms aim to identify a family of solutions lying on the pareto-optimal front of non-dominated solutions. A solution or combination of mitigation methods dominates another solution if it is superior or equal in all objectives (pollutant reductions) but at least superior in one objective. The complete set of non-dominated solutions represents the best available solutions for achieving each

objective. Unlike a single objective optimisation process that identifies a single satisfactory solution, the process therefore aims to evolve a set of solutions that provide answers to the full range of possible target reductions for each pollutant. For this project, the NSGA-II algorithm (Deb et al., 2000) was used. This algorithm was not necessarily the most efficient for this analysis, but has been proven to be effective in a large number of applications and is currently used as a standard in comparisons of algorithms (Coello et al., 2007). Hence it was regarded as robust.

The NSGA-II algorithm is elitist, meaning that the best solutions are preserved at each iteration of the optimisation model. The relative fitness of the solutions was established firstly by the Pareto front on which they lie. The algorithm was designed to seek solutions that minimised cost and maximised the reduction of the chosen pollutants simultaneously. The parents of each child solution were generated by tournament selection. The diversity of solutions along the Pareto front was maintained by implementing a simple crowding operator, where solutions on the same Pareto front were given a higher probability of being selected to reproduce and survive into the next generation if the neighbouring solutions in objective space were more distant.

6.1. *Optimisation properties*

Suitable values for the number of generations in the optimisation procedure and the population size vary depending upon the complexity of the problem (number of pollutants to optimise reductions for and the number of mitigation methods).

For optimisations on only one pollutant, even with all 77 methods active, results using a population of 100 and 100 generations appear comparable to using a more thorough choice of a population of 100 and 400 generations (Figure 4). However, more detailed analysis of the results (Table 12) shows that the maximum separation between the two Pareto fronts in this example was close to 4% (compared with a maximum reduction of 62%). This table also shows the variation in results that occurs between two identically set up optimisations, due to the stochastic nature of the optimisation process, with the maximum difference between two Pareto fronts varying from 3.3% to 4.6%. The maximum difference in this example is only found in a small section of the Pareto curve, elsewhere the curves appear almost identical. However, if the results of a 100 generation run are combined with a 400 generation run and new Pareto fronts found, then only around 10% of the results from the 100 generation run lie on the new first Pareto front, and over 90% of the results from the 400 generation run lie on the first front – thus the majority of the results from the 400 generation optimisation dominate those from the 100 generation optimisation. Thus although using 100 generations produces a reasonable solution when optimising on only one pollutant, and is ideal for assessing the magnitudes of reductions that can be achieved and the shape of the Pareto front, for a more thorough analysis, somewhere in the region of 400 generations would be appropriate. If the problem was made simpler, by only having half as many potentially applicable mitigation methods, then the optimisation using only 100 generations performed more favourably, with a maximum difference between the Pareto fronts of 1.7% (but with a maximum reduction of only 33%), and more importantly, over one third

of the points from the 100 generation optimisation Pareto front lying on the Pareto front created by combining the results with those of an optimisation using 400 generations.

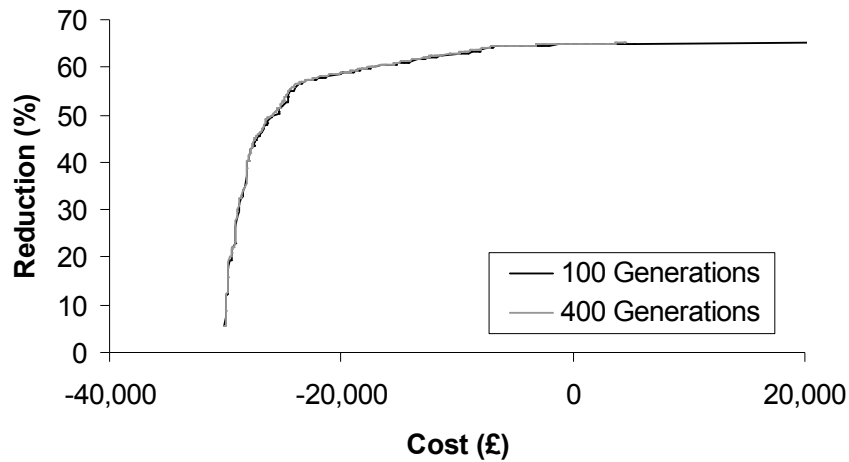


Figure 4 Comparison of Pareto fronts for phosphorus reductions using 100 and 400 generations

Table 12 Maximum differences in % reductions achieved for phosphorus between repeated optimisations using 400 generations and 100 generations

		400 Generations		
		A	B	C
100 Generations	A	4.2%	4.2 %	3.7%
	B	4.6%	4.6%	4.5%
	C	3.9%	3.6%	3.3%

If the problem to solve becomes more complex, then more generations and a bigger population are needed for robust results, but low values can still be used to get an impression of what can be achieved. The following results are for optimising on 4 pollutants (nitrate, phosphorus, ammonia and methane) using all potential mitigation methods and then repeating the optimisation, but only for nitrate. Figure 5 shows the results using a population of 300 and 600 generations. With the multi-pollutant optimisation, we get a cloud of points, representing combinations of methods that are good at reducing one or more pollutants. These can be sieved to find the Pareto front for nitrate reduction, and this can then be compared with the results of optimising on nitrate only. This is shown in Figure 6, which compares the nitrate-optimisation only results with the nitrate reduction Pareto fronts produced from multi-pollutant optimisation using a selection of population sizes and generations. Even with only a population of 100 and 200 generations, a reasonable fit to the nitrate-only optimisation is achieved. With a population of 200 and 400 generations, the maximum difference between the two curves is just under 5%, and with a population of 300 and 600 generations, the maximum difference drops to

1.8%, although the nitrate-only Pareto front still almost entirely dominates the multi-pollutant derived front.

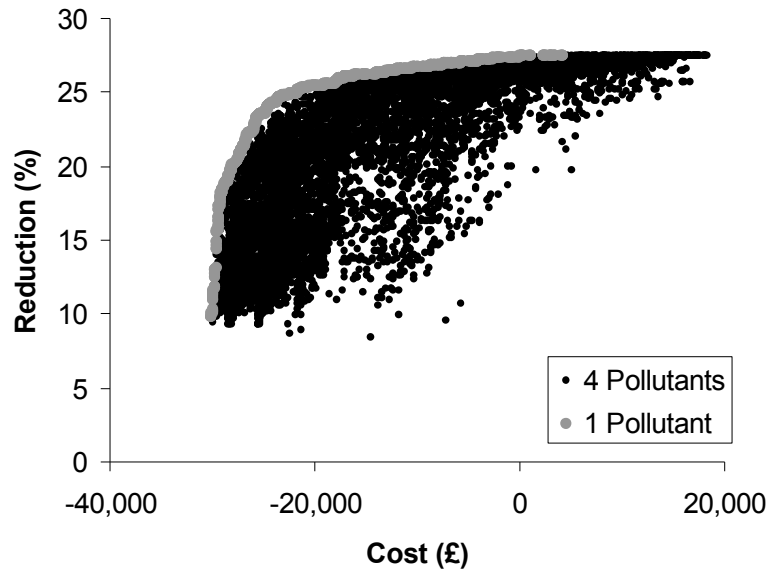


Figure 5 Comparison between results optimising on nitrate only and 4 pollutants including nitrate, using a population of 300 and 600 generations

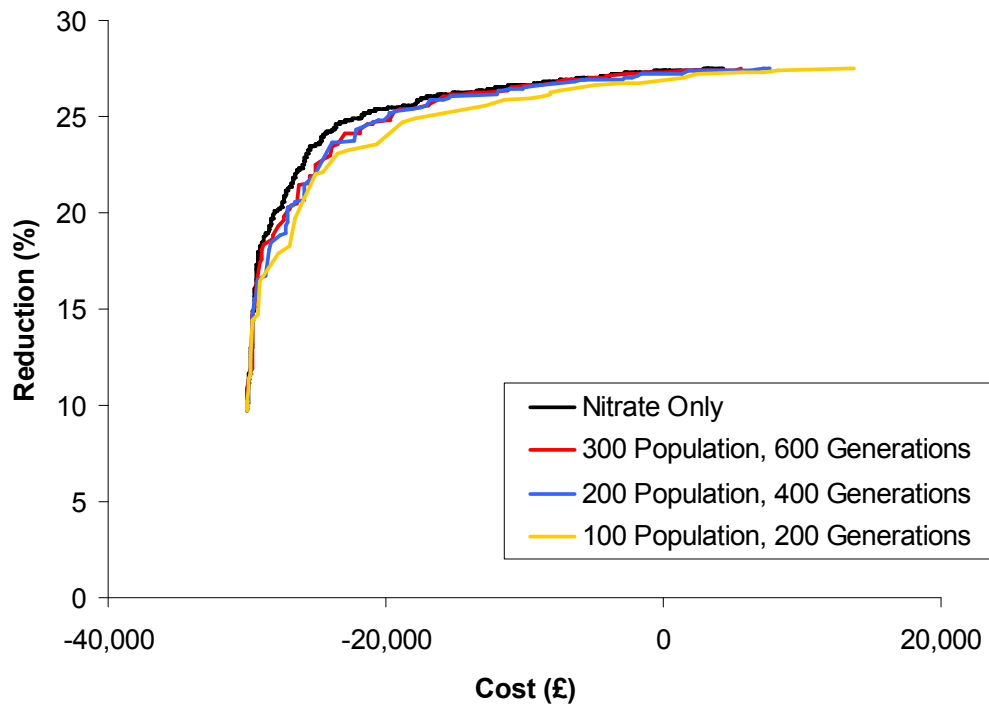


Figure 6 Comparison between Pareto fronts for nitrate reduction achieved when optimising on nitrate only and from a multi pollutant optimisation using different combinations of population size and generations.

With an optimisation problem as complex as the system currently contains - optimising on all 7 pollutants using all available mitigation methods – the optimiser is still able to obtain a reasonable match to the results that can be achieved using single pollutant optimisation (Figure 7). In this example, there are a lot of points which achieve a very limited reduction in nitrate for the same cost at which much greater reductions can be achieved (as mitigation methods which target other pollutants are being chosen). By constraining the minimum acceptable reductions allowed for any pollutant, the search space for the problem would be reduced and thus more results found in areas of interest. Thus for a complex problem such as this, it would be worthwhile performing some quick runs to find the magnitudes of reduction that can be achieved for the different pollutants and use these to constrain the optimisation process. It would also be worthwhile assessing the mitigation methods individually in order to find methods that are not going to help in achieving the desired targets. These can then be removed from the available methods to make the optimisation problem simpler.

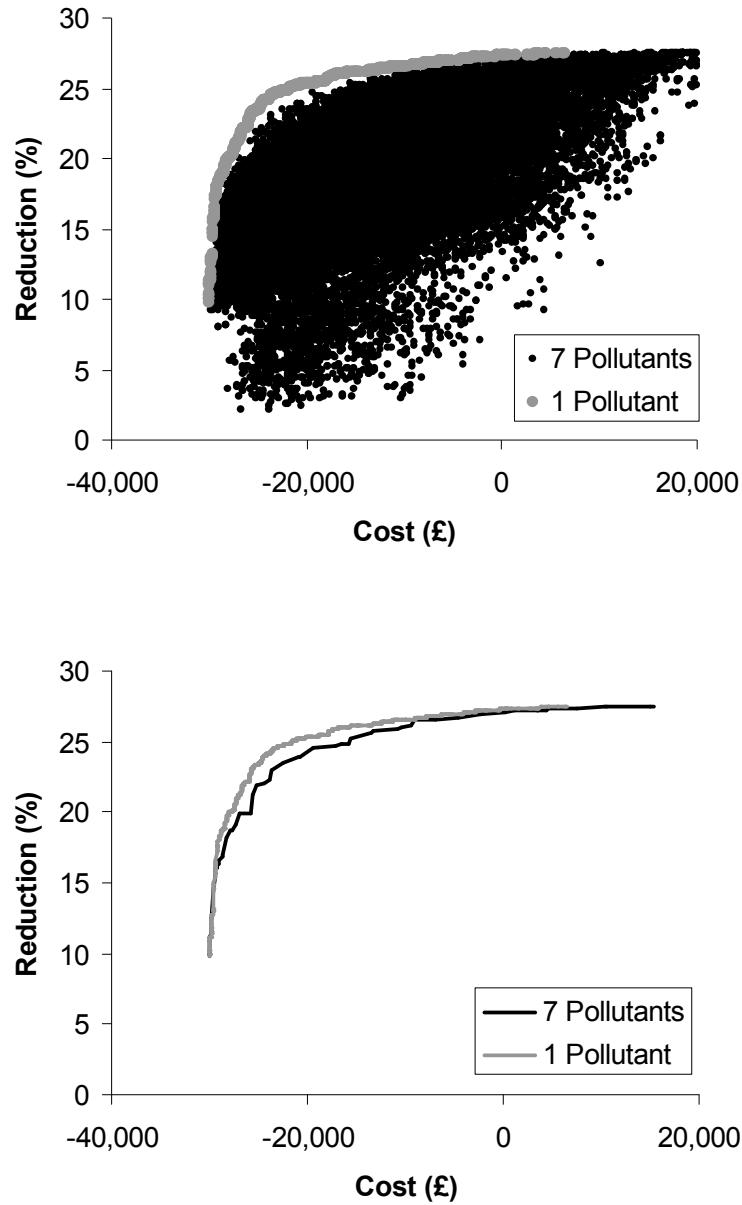


Figure 7 Comparison of all results and Pareto fronts for nitrate reduction, following optimisation on nitrate only, and a multi-pollutant optimisation on 7 pollutants, both using a population of 500 and 1000 generations.

6.2. Optimisation with uncertainty

All of the parts of the framework have an inherent uncertainty associated with them. However, this work only allowed for investigation in the effects of uncertainty in the baseline pollutant losses (Section 4) and the mitigation method impacts (Table 8, Section 5.3).

The minimum and maximum values for the baseline losses and method impacts provided the bounds used in the uncertainty analysis, with the bounds used to describe an area of equal possibility. It was necessary to use an efficient way to sample this possibility space to ensure complete and representative coverage, given the potentially large number of mitigation methods and pollutant loss coordinates would mean that purely random sampling would be impractical. The approach taken was based on Latin Hypercube sampling, first described by McKay et al, (1979) and Imam et al, (1981), and which has been widely used in uncertainty analysis, including environmental pollution studies (e.g. McIntyre and Wheeler (2004); Muleta and Nicklow (2005)).

In Latin hypercube sampling, the possible range of each variable (mitigation method or baseline loss coordinate) is divided into N equally sized segments, and N samples are then taken, one from each segment. This is then repeated for each variable, such that the sampling is not correlated. For mitigation methods, the number of samples, N , is set to the number of generations in the optimisation routine. For the pollutant losses, N is 5 times the number of generations (as there are generally more coordinates for pollutant losses on most farm types than applicable mitigation methods). This means that any sample of mitigation methods would be tested against 5 different pollutant loss scenarios. Uhlenbrook and Sieber (2004) estimate that N should be at least 10 times the number of variables, but quote other estimates of between 2 and 5 times. For this reason, the number of generations in the optimisation generally needs to be larger when uncertainty is being considered, particularly uncertainty in the baseline pollutant losses.

For the baseline losses, there was no correlation between the variation in any one coordinate and another (e.g. the sediment loss from both the surface and preferential pathways could increase) although this does not always reflect a potentially realistic mass-flow concept (e.g. a higher ammonia loss from the stabling could result in less ammonia available for loss from applied manure). For mitigation methods, all of the impact coordinates for a specific method varied in tandem (e.g. all the positive impacts would increase by 20% and any negative impacts would increase by 20%), representing the whole method being more or less effective, rather than the method being more or less effective against any individual target coordinate.

7. FARMSCOPER

The project has created a pair of spreadsheets (created in Microsoft Excel 2003) linked to a database (created in Microsoft Access 2003), that enable the user to assess the pollutant losses on a farm, assess the impacts of mitigation methods on the losses from that farm and find a suite of optimal solutions of mitigation methods to achieve differing levels of pollutant reduction.

A detailed user guide for FARMSCOPER is provided in Appendix 1. The following subsections briefly describe the features and capabilities of the framework. A sample of the results and analysis possible are presented in Section 8.

7.1. Farm Creator

The farm creator spreadsheet enables the user to select one of the farm types described in Section 3, as well as one of the 3 soil types and 6 climate zones. The pollutant losses for each of the pollutants considered are then generated, and are presented in both a comprehensive tabulated format and via a set of paired graphs that allow easy comparison and analysis of the key areas and sources for the different pollutants.

7.1.1. Modifying the default farms

The farm creator spreadsheet also allows the user to modify the following features of the default farms:

- Livestock numbers
- Crop areas
- N and P fertiliser inputs
- Pesticide inputs

Due to the underlying assumptions about farm practice within the different farms, modifications are limited to scaling the pre-existing features on the farm type selected, e.g. the number of dairy cows or arable land can be altered on the dairy farm, but it is not possible to add poultry to the farm. Modifications for livestock are applied to headline numbers (e.g. adult dairy) and then the rest of the livestock (e.g. dairy followers) are scaled accordingly. Modifications to crop areas and fertiliser and pesticide inputs are applied proportionately across all crop types found on the farm type.

7.2. Farm Evaluator

The farm evaluator spreadsheet enables the user to load a farm created with the farm creator spreadsheet and assess the costs and effects of a suite of mitigation methods.

Several methods have a negative cost of implementation, generally representing savings to the farmer through reduced fertiliser application. It may not be desirable to try and use these savings to offset the costs of other

expensive methods, thus there is the option to ignore any cost savings (the methods will be implemented at zero cost).

7.2.1. Impacts of individual mitigation methods

The user can select any number of the mitigation methods, and assess the cost and overall impact of each method applied individually against each of the different pollutants. The impacts of any prior implementation of methods can also be seen.

7.2.2. Impacts of multiple mitigation methods

The user can select any number of mitigation methods and find out the cost and effect of the mitigation methods being applied together. This produces not only the overall impacts against the different pollutants, but also the impacts against all of the individual coordinates of the pollutant losses on that farm. The impacts of any prior implementation of methods can also be seen.

7.2.3. Impacts of method uncertainty

The user can select any number of mitigation methods and find the sensitivity of the overall pollutant reductions to the uncertainty in the individual method impacts.

7.2.4. Comparison of losses for different scenarios

The detailed output described in Section 7.2.2 can be stored within the spreadsheet for multiple suites of mitigation methods. The spreadsheet provides functionality to compare the impacts of the different suites of mitigation methods by both pollutant and area. It is also possible to load more farms from the farm creator spreadsheet and compare the impacts of (potentially different) suites of mitigation methods on different farm types or farms on different soil types or climate zones.

7.2.5. Optimisation of mitigation methods

The spreadsheet can be used to assess the optimal sets of methods to apply from a given selection of methods. This optimisation can be for any number of pollutants, with optional constraints to force the optimisation algorithm to meet certain target reductions for each pollutant. The results of the optimisation are the suites of methods which are pareto-optimal solutions, as described in Section 6. For optimisation against only one pollutant (and cost), the first pareto front is comparable to a cost curve. The spreadsheet provides functionality to compare the impacts of the optimal sets of methods against each pollutant and cost. Optimisation is performed relative to the level of pollution after prior implementation of methods has been accounted for.

The optimisation process allows for competition and dependency between methods, as well as grouping of methods.

7.2.6. Optimisation with uncertainty

7.2.7. New methods

The methods currently within the spreadsheet are a non-exhaustive list of potential methods, using the best data currently available to quantify both their impacts and costs. The evaluator spreadsheet allows these methods to easily be altered should more evidence become available, or for more methods to be added to the current list.

8. Results

The framework created can be used to investigate the pollutant losses and impacts of mitigation methods for each of the different farm types, on the different soil types under different climates. The purpose of this results section is not to show detailed output for every farm type, but to pull out some of the contrasts between the farm types, outline the impacts of mitigation methods against different pollutants, and demonstrate the functionality of the framework that has been created.

8.1. Pollutant losses

For water borne pollutants, it is important to understand how the delivery vectors (transported sediment and drainage) vary between the different climate zones and soil types. Table 13 shows this variation for the mixed farm, but the contrasts are similar for all farm types. For an identical soil type, the amounts of drainage and sediment transported are higher for arable land than for grassland – this is because grassland is present all year round, whereas there are periods of bare soil during arable cultivation. Grassland is thus more protected from erosion and also causes greater evapotranspiration. Artificial drainage is an efficient conduit for the transport of sediment, thus grassland on impermeable soil types with artificial drainage generally has much higher rates of sediment loss than grassland on permeable soil types, proportionately more so at lower drainage amounts (10-20 times for the '< 600 mm' climate, only 3-4 times for the '> 1500 mm' climate). On the impermeable soil type where grassland isn't artificially drained, erosion rates are comparable to those on the permeable soil type. The importance of artificial drainage towards the amount of sediment lost is a key factor when determining the usefulness of different mitigation methods – methods that impact against runoff only, such as riparian buffer strips, will be significantly more effective on a permeable soil type, where the majority of the sediment is lost via the surface, than on a drained soil type, where the majority of the sediment is lost in preferential flow through the drains.

The appropriateness of mitigation methods for a farm type is also related to the importance of different sources on the farm. A limited apportionment of the pollution on the mixed farm (in the 600-700 mm climate, impermeable – drained arable soil type) is shown in Figure 8. The vast majority of sediment is lost from the arable parts of the farm, which can be deduced from Table 13, as the farm is almost one third arable and only the arable fields are drained. Soil associated phosphorus loss is responsible for one third of total phosphorus loss, mainly from the arable areas, although manure and excreta are also important, particularly the storage of manure and transport of animals. For nitrate, losses from the grassland area are almost as high as those from arable (although rates per ha of arable land would be higher). Grassland receives negligible amounts of pesticides, so arable land and losses occurring on the steading (during filling, mixing and cleaning of the spraying equipment) are dominant. Nitrous oxide losses are caused in roughly equal measure on this farm by fertilisers, manures and excretion at grazing, so grassland is the dominant source area, due to its greater spatial extent on

the farm. The majority of the ammonia losses are from livestock housing and the storage of manure, so the farmstead itself is the dominant source area for ammonia emissions, although losses from manure applied to land are also important. Methane losses are dominated by enteric emissions, so the farmstead and grassland areas are the major source areas. Note that these losses do not take any prior implementation of mitigation methods into account, and thus represent an over-estimation of current pollutant losses.

Table 13 Hydrology and sediment losses on the mixed farm type

Soil Type	Annual Rainfall (mm)	Arable		Grass	
		Drainage (mm)	Sediment (kg ha ⁻¹)	Drainage (mm)	Sediment (kg ha ⁻¹)
Permeable	< 600	160	10	100	5
	600 – 700	230	15	170	10
	700 – 900	360	70	350	50
	900 – 1200	560	200	560	110
	1200 – 1500	810	360	800	170
	> 1500	1010	890	1130	300
Impermeable: Drained for Arable Use	< 600	170	120	100	5
	600 – 700	230	210	170	20
	700 – 900	350	680	290	90
	900 – 1200	530	1240	490	140
	1200 – 1500	790	1800	740	160
	> 1500	1070	2130	1200	250
Impermeable: Drained for Arable and Grassland	< 600	180	190	120	70
	600 – 700	240	340	180	180
	700 – 900	350	690	300	320
	900 – 1200	550	1120	560	630
	1200 – 1500	760	1450	740	840
	> 1500	1080	3240	1150	1720

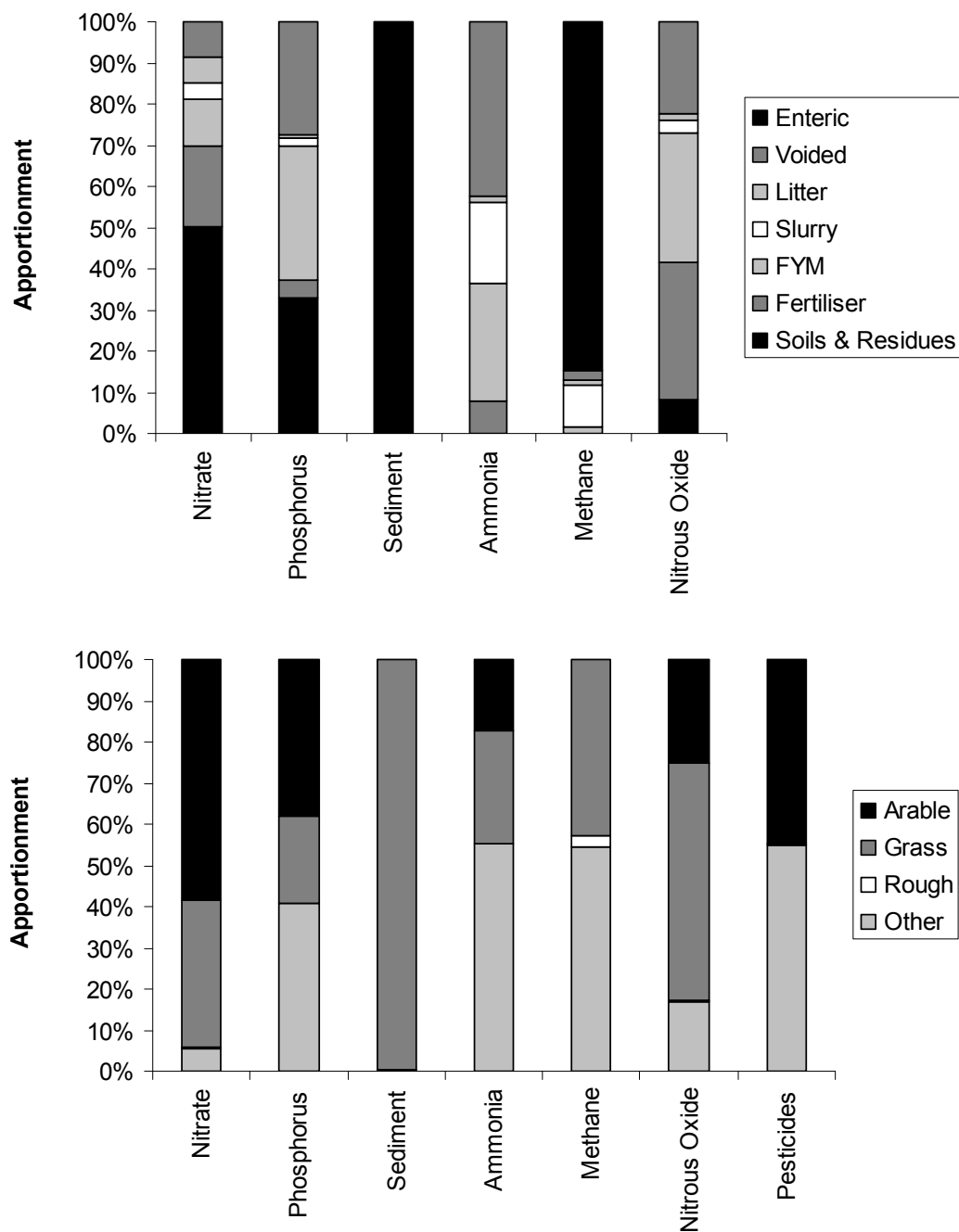


Figure 8 Apportionment of baseline losses for each pollutant on the Mixed farm type with the 600-700 mm climate on the impermeable – drained arable soil type.

Unsurprisingly for a mixed farm, the levels of the different pollutant losses occurring are average when compared with those from all farm types (Table 14). Sediment loss is highest on the outdoor pig farm (337 kg ha^{-1}), where the grazing of pigs creates large areas of bare soil, which are prone to significant soil erosion. This high loss of sediment, in combination with lots of excreta from the pigs on the bare soil also means that the outdoor pig farm has the highest rates of phosphorus loss (2.5 kg ha^{-1}). Of the other farms, it is those

with more arable land that have the higher sediment losses, although phosphorus losses are highest on those with both large amounts of manure and arable land (0.6 kg ha^{-1} on the cereal farms importing manure). The lowest levels of sediment loss (under 30 kg ha^{-1}) and phosphorus loss (0.2 kg ha^{-1}) are on the grazing farms, where stocking rates are not too high and there is limited arable land.

Nitrate losses are highest on the farms receiving the most manure and lowest on those with limited arable land at c. 50 kg ha^{-1} and less than 10 kg ha^{-1} respectively. Pesticide losses on the arable farms (over $0.10 \text{ units ha}^{-1}$) are significantly higher than those on the grazing and dairy farms, with horticultural farms, which apply the most pesticides, having the greatest losses ($0.25 \text{ unit ha}^{-1}$).

Nitrous oxide losses are primarily caused by manures, fertilisers and excretion, so losses are highest on the arable farms importing manure ($10\text{-}15 \text{ kg ha}^{-1}$) and lowest on the more extensive grazing farms and the arable farms without manure (under 7 kg ha^{-1}). Methane losses are primarily caused by enteric emissions from dairy animals, so the dairy farm has significantly higher losses than other farm types (187 kg ha^{-1}). Storage of slurries and poultry muck are also responsible for significant methane emissions, so the indoor pig farm (where slurry is stored beneath the pig housing) and the cereal farm receiving poultry manure (which is stacked in field heaps on the farm) also have high losses, as does the mixed farm, since it has dairy animals, pigs and poultry.

Ammonia losses are high on the farms with significant manure ($37 \text{ to } 96 \text{ kg ha}^{-1}$) and low on the rest (under 11 kg ha^{-1}). These contrasts for the gases losses between farm types remain the same for all soil types and climate zones, as losses are assumed to be independent of the environment. Nitrate losses are source limited - as there is only a limited supply of nitrate in the soil – so the increases in nitrate loss with drainage become smaller for the wetter climate zones (Figure 9). Wetter climates are also more likely to have soils prone to de-nitrification, which can reduce the losses of nitrate from grassland, hence the slight decrease in nitrate losses shown in Figure 9. Variations in phosphorus and sediment losses for a given farm type are controlled by the relative importance of surface and lateral flow pathways (and thus the presence of artificial drainage). Sediment loss variation has been shown in Table 13, while phosphorus losses are shown in Table 15.

On the permeable soil type, the vast majority of the water ends up as groundwater, which the PSYCHIC model assumes to contain negligible amounts of phosphorus, whereas for the heaviest soil types, the vast majority of the water is transported laterally, and this is able to transport significant amounts of phosphorus (both dissolved and attached to sediment particles) – thus there is almost a ten-fold variation in phosphorus loads from land for the dairy farm in this one climate zone depending upon the soil type (losses from steadings and due to cattle access to streams whilst travelling to the fields are not explicitly dependent upon soil type, but do vary slightly due to the location of the soil types within the climate zone, see).

Table 14 Baseline losses for the different farm types for the ‘impermeable – drained arable’ soil and 600-700 mm climate zone. Losses are expressed as kg, except for pesticides, which are expressed in full dose units. Note that the indoor pig and poultry farms have no associated land.

Total losses	Nitrate	Phosphorus	Sediment	Ammonia	Methane	Nitrous Oxide	Pesticides
Dairy	1,859	38	4,718	4,333	21,217	1,126	0.6
LFA - Grazing	753	11	1,145	718	6,717	463	0.0
Lowland - Grazing	875	19	2,927	1,155	7,127	590	0.4
Mixed	3,076	52	13,112	5,815	12,998	1,496	4.5
Outdoor Pig	2,816	142	19,212	410	902	591	4.4
Indoor Pig	-	-	-	7,673	17,661	69	-
Poultry	-	-	-	9,548	-	-	-
Roots & Comb.	4,496	61	37,782	989	0	1,018	24.2
Roots & Comb. + Poultry Muck	7,564	63	37,782	8,988	2,378	1,751	24.2
Mixed Comb.	4,722	62	39,452	1,331	-	1,336	21.8
Mixed Comb. + Pig Manure	9,191	117	39,452	15,392	449	2,634	21.8
Winter Comb.	4,037	49	31,045	1,223	-	1,165	19.3
Winter Comb. + Pig Manure	8,263	102	31,045	15,285	449	2,463	19.3
Horticulture	337	4	2,463	70	0	65	4.4
Per ha of farmland							
Dairy	16	0.3	42	38	187	10	0.01
LFA - Grazing	5	0.1	8	5	46	3	0.00
Lowland - Grazing	9	0.2	29	11	71	6	0.00
Mixed	20	0.3	84	37	83	10	0.03
Outdoor Pig	49	2.5	337	7	16	10	0.08
Indoor Pig*	-	-	-	-	-	-	-
Poultry*	-	-	-	-	-	-	-
Roots & Comb.	25	0.3	210	5	0	6	0.13
Roots & Comb. + Poultry Muck	42	0.4	210	50	13	10	0.13
Mixed Comb.	24	0.3	200	7	-	7	0.11
Mixed Comb. + Pig Manure	47	0.6	200	78	2	13	0.11
Winter Comb.	25	0.3	195	8	-	7	0.12
Winter Comb. + Pig Manure	52	0.6	195	96	3	15	0.12
Horticulture	19	0.2	137	4	0	4	0.25

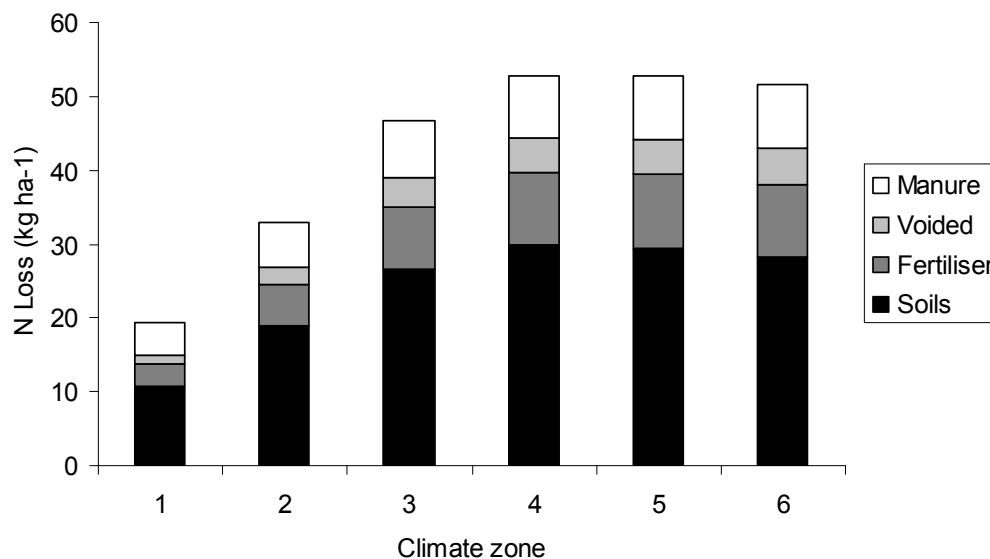


Figure 9 Variation in N losses with climate zone for the Mixed Livestock farm type on a permeable soil. Some source apportionment is shown

Table 15 Variation in P losses and hydrology with soil type for the Dairy farm type in 600-700 mm climate zone.

Soil Type	Land Use	P Loss (kg)	Flow Pathways		
			Surface	Lateral	Groundwater
Impermeable - Arable and Grassland Drained	Arable	9.8	3%	96%	1%
	Grass	92.2	3%	96%	1%
	Rough	0.0	3%	0%	97%
	Other	16.3	-	-	-
Impermeable - Arable Drained	Arable	6.2	5%	61%	34%
	Grass	16.4	4%	0%	96%
	Rough	0.0	4%	0%	96%
	Other	15.8	-	-	-
Permeable	Arable	0.4	3%	0%	97%
	Grass	10.2	3%	0%	97%
	Rough	0.0	3%	0%	97%
	Other	14.8	-	-	-

8.2. Individual mitigation method implementation

It is possible to view the impacts of each method in turn for any farm type, which helps assess the methods which are most important for controlling each pollutant. The framework created is designed to do this - the results in Table 16 show sample output for this on the dairy farm ('impermeable – drained arable' soil and 600-700 mm climate zone, as per Table 14). It is important to

remember that these results do not account for prior implementation of mitigation methods, which is discussed in the following section.

The impact of multiple mitigation methods is not the same as the sum of the individual mitigation methods, as summing the effects does not take account of the interaction between methods where they both target the same source, or where the application of methods is in direct competition.

For the dairy farm, the results from FARMSOPER predicted that the most effective way of reducing sediment loss was through improved soil management, such as 'Adopt reduced cultivation systems' (method 7), which achieved a 17% reduction in sediment losses. Phosphorus losses were also tackled by improved soil management, but improved manure management was also important (e.g. methods 70, 71 and 73), as was preventing livestock having access to water. The results also predict that using artificial wetlands was effective at reducing phosphorus losses from steading runoff on this farm type, due to the amount of time dairy animals spend on the steading. Similar methods were predicted as being effective for nitrate loss mitigation, although 'Establish cover crops in the autumn' (method 4) and 'Use plants with improved nitrogen use efficiency' (method 20) also have very good potential for nitrate loss mitigation. For methane, 'Allow cattle slurry stores to develop a natural crust' (method 57) was predicted to be the most effective. The methods to reduce or extend the grazing season had proportional but opposite impacts for methane (reduce: -6%, increase +6%). Altering the grazing season was similarly important for ammonia, depending upon whether it was reduced or extended, but improved manure management and housing options also had significant impacts on ammonia losses. The biggest impacts on nitrous oxide, 17% and 8%, were from 'Use clover in place of grass' (Method 31) and 'Do not spread slurry at high-risk times' (method 71) respectively. Pesticide losses were altered by some of the methods primarily targeting soil management, but the biggest impacts were from the pesticide specific methods - improving handling of the pesticides on the farmstead (up to 27% reductions) and preventing spray drift (8%).

Costs for method implementation were as high as £7,400 for the whole farm, although many methods are considerably less. A few methods, such as those that reduce the amount of fertiliser required, resulted in a net saving for the farm. These included 'Integrate fertiliser and manure nutrient supply' (Method 23) and 'Use clover in place of grass' (method 31).

Table 16 Cost and % reduction for maximum implementation of each individual method relative to the baseline of no prior method implementation on the Dairy farm type, for the 'impermeable – drained arable' soil type and 600 – 700 mm climate.

ID	Method	Cost (£)	Nitrate	Phosphorus	Sediment	Ammonia	Methane	Nitrous Oxide	Pesticides
4	Establish cover crops in the autumn	440	5.2	1.5	9.7	-	-	-	0.8
5	Early harvesting and establishment of crops in the autumn	3,900	2.1	0.5	3.2	-	-	-	0.1
6	Cultivate land for crops in spring rather than autumn	1,050	1.5	0.9	5.6	-	-	-	0.2
7	Adopt reduced cultivation systems	-500	0.1	1.0	16.5	-	-	0.1	1.4
8	Cultivate compacted tillage soils	50	0.3	3.9	16.5	-	-	-	2.1
9	Cultivate and drill across the slope	90	0.1	0.1	1.2	-	-	-	1.2
10	Leave autumn seedbeds rough	40	0.0	0.0	0.1	-	-	-	0.0
11	Manage over-winter tramlines	30	0.0	0.0	0.3	-	-	-	0.3
13	Establish in-field grass buffer strips	60	0.0	0.1	1.6	-	-	0.1	1.6
14	Loosen compacted soil layers in grassland fields	950	0.1	6.6	8.4	-	-	-	0.0
15	Establish riparian buffer strips	130	0.1	0.4	3.2	0.0	-	0.1	0.1
16	Allow field drainage systems to deteriorate	1,580	3.3	0.3	1.2	-	-	-	0.4
19	Make use of improved genetic resources in livestock	-6,500	0.6	1.0	-	9.2	2.0	1.2	-
20	Use plants with improved nitrogen use efficiency	-1,200	6.4	-	-	0.8	-	3.7	-
21	Fertiliser spreader calibration	110	1.3	0.1	-	-	-	0.7	-
22	Use a fertiliser recommendation system	-600	2.0	0.4	-	0.8	-	3.7	-
23	Integrate fertiliser and manure nutrient supply	-19,870	0.4	0.7	-	0.8	-	3.7	-
25	Do not apply fertiliser to high-risk areas	110	0.6	0.7	-	0.2	-	0.7	-
26	Avoid spreading fertiliser to fields at high-risk times	110	0.4	0.4	-	0.2	-	-	-
27	Fertiliser placement	30	0.0	0.0	-	0.0	-	-	-
290	Replace urea fertiliser to grassland with another form (e.g. ammonium nitrate)	-30	-	-	-	0.1	-	-	-
291	Replace urea fertiliser to arable land with another form (e.g. ammonium nitrate)	-10	-	-	-	0.2	-	-	-
300	Incorporate a urease inhibitor into urea fertilisers for grassland	0	-	-	-	0.1	-	-	-

ID	Method	Cost (£)	Nitrate	Phosphorus	Sediment	Ammonia	Methane	Nitrous Oxide	Pesticides
301	Incorporate a urease inhibitor into urea fertilisers for arable land	0	-	-	-	0.1	-	-	-
31	Use clover in place of grass	-5,700	0.3	-	-	3.4	-	17.1	-
32	Do not apply P fertilisers to high P index soils	-540	-	1.9	-	-	-	-	-
331	Reduce dietary N and P intakes: Dairy	4,580	2.9	6.1	-	8.3	1.7	0.5	-
35	Reduce the length of the grazing day/grazing season	4,980	0.6	3.0	3.4	-13.5	-5.8	2.1	-
36	Extend the grazing season for cattle	1,640	-0.1	-0.6	-0.7	13.5	5.8	-2.1	-
37	Reduce field stocking rates when soils are wet	4,980	0.6	3.0	3.4	-5.4	-5.8	2.1	-
38	Move feeders at regular intervals	950	0.1	0.7	3.4	-	-	-	-
39	Construct troughs with concrete base	480	0.1	0.7	-	-	-	-	-
41	Improved feed characterisation	0	0.6	1.0	-	1.8	2.0	1.2	-
44	Increase scraping frequency in dairy cow cubicle housing	5,090	-	-	-	9.1	-	-	-
45	Additional targeted bedding for straw-bedded cattle housing	2,870	-	-	-	11.7	-	-	-
46	Washing down of dairy cow collecting yards	1,270	-	-	-	7.9	-	-	-
54	Increase the capacity of farm manure (slurry) stores	2,160	0.4	1.5	-	-0.7	-	-	-
55	Adopt batch storage of slurry	7,410	-	-	-	-0.7	-	-	-
56	Install covers to slurry stores	1,850	-	-	-	2.0	-	-	-
57	Allow cattle slurry stores to develop a natural crust	280	-	-	-	2.0	11.8	-	-
59	Minimise the volume of dirty water produced	3,120	0.4	1.5	-	-	-	-	-
61	Compost solid manure	680	-	-	-	0.1	-	-	-
62	Store solid manure heaps away from watercourses/drains	30	0.3	2.4	-	-	-	-	-
63	Store solid manure heaps on concrete and collect effluent	140	0.3	2.4	-	-	-	-	-
64	Cover manure stores with polythene sheeting	150	0.1	0.5	-	0.0	-	-	-
65	Liquid/solid manure separation	1,850	0.1	0.3	-	0.7	-	-	-
69	Manure Spreader Calibration	220	0.1	0.4	-	-	-	0.1	-
70	Do not apply manure to high-risk areas	210	1.0	4.0	-	-	-	-	-
71	Do not spread slurry at high-risk times	190	1.9	7.7	-	-	-	7.6	-

ID	Method	Cost (£)	Nitrate	Phosphorus	Sediment	Ammonia	Methane	Nitrous Oxide	Pesticides
72	Slurry band spreading application techniques	2,780	-	-	-	14.5	-	-	-
73	Use slurry injection techniques	3,700	0.9	7.7	-	23.2	-	-	-
74	Do not spread FYM to fields at high-risk times	30	0.3	1.7	-	-	-	-	-
75	Incorporate manure into the soil	270	0.1	2.8	-	0.5	-	-	-
78	Fence off rivers and streams from livestock	950	1.6	13.1	-	-	-	-	-
79	Construct bridges for livestock crossing rivers/streams	950	1.3	10.4	-	-	-	-	-
80	Re-site gateways away from high-risk areas	220	0.1	2.8	4.0	-	-	-	-
81	Farm track management	270	-	0.2	-	-	-	-	-
82	Establish new hedges	810	0.0	0.2	0.2	0.0	-	0.1	0.0
83	Establish and maintain artificial wetlands - steadying runoff	1,870	0.5	5.8	-	-	-	-	-
90	Calibration of sprayer	220	-	-	-	-	-	-	0.6
91	Fill/Mix/Clean sprayer in field	50	-	-	-	-	-	-	27.2
92	Avoid PPP application at high risk timings	310	-	-	-	-	-	-	2.1
94	Drift reduction methods	30	-	-	-	-	-	-	8.2
95	PPP substitution	30	-	-	-	-	-	-	2.9
96	Construct bunded impermeable PPP filling/mixing/cleaning area	50	-	-	-	-	-	-	27.2
97	Treatment of PPP washings through disposal, activated carbon or biobeds	50	-	-	-	-	-	-	13.6

8.3. Impact of prior implementation of mitigation methods

A true estimate of current pollutant losses requires prior implementation of mitigation methods to be taken in to account. Implementation of the default methods varied between 0 and 80% (Table 11). When the impacts of these on the baseline pollutant losses were calculated, there was a reduction in pollutant losses (for the 'impermeable – drained arable' soil and 600-700 mm climate zone, as used for baselines losses shown in Table 14) of up to 15% (Table 17). Highest reductions were for pesticides (13-15%), whilst lowest reductions were for methane and nitrous oxide (less than 3%). Reductions in ammonia were higher on the dairy and pig and poultry farms, mainly as a result of 'Reduced dietary nitrate and phosphorus intakes' (methods 331 and 332; both 80% prior implementation) and 'Allow cattle slurry stores to develop a natural crust' (method 57; 80% prior implementation). The reduced dietary intakes also meant reductions in phosphorus and nitrate were higher on the dairy, mixed livestock and outdoor pig farms (10% and 5% respectively).

Table 17 Cost and effect of prior implementation of methods on the different farm types for the 'impermeable – drained arable' soil and 600-700 mm climate zone.

	Cost (£)	Nitrate	Phosphorus	Sediment	Ammonia	Methane	Nitrous Oxide	Pesticides
Dairy	1,600	4	12	7	14	10	3	14
LFA - Grazing	-40	1	8	4	0	0	1	14
Lowland - Grazing	10	2	9	6	0	0	1	14
Mixed	1,890	4	11	8	8	1	2	13
Outdoor Pig	3,280	6	10	5	6	2	2	13
Indoor Pig	7,920	-	-	-	10	2	2	-
Poultry	710	-	-	-	10	-	-	-
Roots & Comb.	2,750	2	5	9	3	-	2	13
Roots & Comb. + Poultry Muck	-3,900	2	6	9	1	0	2	13
Mixed Comb.	3,190	2	5	9	3	-	2	13
Mixed Comb. + Pig Manure	-3,810	2	5	9	1	0	2	13
Winter Comb.	2,540	2	5	9	3	-	2	13
Winter Comb. + Pig Manure	-4,460	1	4	9	1	0	2	13
Horticulture	240	2	5	8	3	-	3	15

The cost of this prior implementation varied dramatically by farm type. On the dairy and pig farms, the reduced dietary intakes of nitrate and phosphorus resulted in significant costs. On the arable farms, significant costs were incurred by a few methods that are costed in terms of their impact on arable productivity and those involving reductions in the use of pesticides. However,

significant savings were made through 'Using a fertiliser recommendation system' and 'Integrating fertiliser and manure nutrient supply' (methods 22 and 23; 25% prior implementation) due to reduced expenditure on fertilisers. Thus the cereal farms without manures had a cost of prior implementation of £2,500 to £3,500, but those importing manure had a saving of around £4,000. Implementation of these two methods (22 and 23) was assumed to be more common on farms within NVZs than those outside (80% versus 25%: Table 11), which would have a strong impact on the savings made under prior implementation. This is why guidance was provided for the extent of prior implementation on farms within NVZs (Table 11).

The impacts of prior implementation for water borne pollutants varied with climate zone and soil type, although reductions were still of comparable size. The cost of prior implementation, and the reductions for the gaseous pollutants, did not vary by climate zone and soil type.

8.4. Impact of full implementation of mitigation methods

The cost and effect of maximum implementation represents the maximum potential for pollutant control using the available methods. Note that where methods are competitive, the method with higher priority was implemented.

For the same climate zones and soil types used before (Table 14 and Table 17), the impacts of combined full implementation are shown in Table 18. The pattern of costs was broadly the same as before, with the dairy and pig farms using expensive methods to reduce pollution, and the arable farms importing manure able to offset any costs through reduced fertiliser usage. The most expensive methods for arable land were 'Establish cover crops in the autumn', 'Early harvesting and establishment of crops in the autumn' and 'Cultivate land for crops in spring rather than autumn' (methods 4, 5 and 6). None of these methods were applicable to the winter combinable farm (as they all require spring cropping), so this had the lowest cost of implementation of the arable farms. On livestock farms, FARMSOPER results predicted considerable savings in fertiliser usage through 'Use clover in place of grass' (method 31), which helped to offset the costs of other methods. In the dairy farm, where methods are shown in detail (Table 16), this method had a saving of almost £6,000.

Reductions in pollution for full implementation were considerable for some pollutants. Pesticide losses were reduced by almost 50% on all farm types, primarily due to tackling losses occurring on the farmstead. Reductions in methane were negligible for all farm types except those with grazing livestock, where the results predicted that a 3-4% decrease beyond the impacts of prior implementation was possible. FARMSOPER results predicted that it was possible to reduce nitrous oxide losses by between 15 and 20% on most farm types, but on the dairy farm results predicted a 35% reduction due to large areas of originally heavily fertilised grassland and large amounts of dairy slurry (fertiliser rates were reduced through implementation of method 31 - 'Use clover in place of grass' – and slurry application timings were improved through method 71 - 'Do not spread slurry at high-risk times'). Ammonia reductions were greatest on the dairy and indoor pig farms, due to method 45 ('Additional targeted bedding for straw-bedded cattle housing') and slurry

application management methods on the dairy farm and improved housing on the indoor pig farm. Although ammonia reductions are large on the arable farms not importing manure (35%), this is relative to an initial low level of pollution.

Results from FARMSCOOPER predicted that sediment losses could be reduced by between 30% and 60%, mainly through reduced and targeted cultivation methods. For phosphorus a combination of many methods contributed towards a similar 30-60% reduction. Nitrate reductions of over 30% were predicted on arable farms, where it is possible to 'Establish cover crops in the autumn' (method 4) and perform 'Early harvesting and establishment of crops early in the autumn (method 5) to reduce the amount of soil nitrate available for leaching over the winter. Reductions in nitrate leaching were lowest on the grazing farms, particularly the extensive grazing on the LFA farm (12%).

Table 18 Cost and % reduction of maximum implementation of methods, relative to prior implementation, on the different farm types for the 'impermeable – drained arable' soil and 600-700 mm climate zone.

	Cost (£)	Nitrate	Phosphorus	Sediment	Ammonia	Methane	Nitrous Oxide	Pesticides
Dairy	28,160	28	65	55	58	0	35	45
LFA - Grazing	-60	12	56	44	13	4	16	49
Lowland - Grazing	3,820	24	63	49	14	4	19	47
Mixed	15,760	32	61	50	25	3	20	46
Outdoor Pig	3,160	17	30	34	21	0	7	46
Indoor Pig	44,810	-	-	-	51	0	0	-
Poultry	640	-	-	-	7	-	-	-
Roots & Comb.	32,230	45	46	52	35	-	18	44
Roots & Comb. + Poultry Muck	8,000	43	49	52	15	0	14	44
Mixed Comb.	17,870	38	41	48	35	-	17	45
Mixed Comb. + Pig Manure	2,850	33	36	48	14	0	16	45
Winter Comb.	11,010	34	39	46	35	-	18	46
Winter Comb. + Pig Manure	-4,080	28	33	46	14	0	17	46
Horticulture	1,570	43	45	51	33	-	26	44

The results were sensitive to the choice of which method has priority when there is competition between methods. 'Reduce the length of the grazing day/grazing season' (method 35) was used in these results, which caused a significant net increase in ammonia and methane emissions. If the opposite method had been chosen, then there would have been much greater

reductions in ammonia and methane, but at the expense of the other pollutants.

It is worth bearing in mind that some of the mitigation methods used in this scenario would meet a lot of resistance from the farming community (e.g. 'Establish cover crops in the autumn') or have a great deal of uncertainty over their impact (e.g. 'Make use of improved genetic resources in livestock' (Method 19) and 'Use plants with improved nitrogen use efficiency' (Method 20)).

8.5. Optimisation of mitigation method selection

The multi-objective optimisation procedure described in Section 6 can be used to find combinations of methods which lie on the pareto-front, representing optimal combinations of methods for one or more objectives (pollutants and cost). For a single pollutant, the results are comparable to a 'cost-curve' (e.g. Figure 10), although the points on the pareto-front with increasing cost do not correspond to the gradual addition of more and more methods to the solution combination. This is because a point on the pareto-front may, for example, represent a solution with one expensive but effective method, whilst its near neighbour may be a group of methods each of which are moderately effective and expensive.

Figure 10 shows two pareto-fronts following optimisation on nitrate reduction for the mixed combinable farm with and without manure. This highlights the point about the savings that can be made through improved use of fertilisers and integration with manure management – the pareto-fronts are similarly shaped for both farms, but the farm with manure is able to offset the costs of method implementation through reduced fertiliser costs.

Note that the optimisation routine always attempts to select mitigation methods that produce savings, even if they do not reduce the pollutant being targeted by the optimisation, as this will enable greater reductions at less cost than if the methods with savings were not selected.

It may not be considered acceptable to use the savings achieved through reduced inputs associated with some mitigation methods (through reduced labour, machinery hours and physical resources) to offset additional costs of other mitigation methods. Thus the tool has the ability to set methods with a cost saving to be cost neutral. In the optimisation procedure, this can alter the order in which methods are implemented, which can not only offset the Pareto front so as to be more expensive, it can also change the shape of the Pareto front, particularly towards the end where fewer methods are selected.

It is also interesting to look at the results of the optimisation for a single farm type and soil type under different climatic conditions (Figure 11). Although the proportional reductions due to the implementation of sets of method were the same for each coordinate, the relative contribution of each coordinate to the total nitrate loss varies with the climate zone. For example, if losses from the soil make up 25% of the total loss on one farm, but 50% of the total loss on another farm, then the net effect of a method reducing the soil loss by 50% would only be a 12.5% reduction in the total loss on the former, but a 25% reduction on the latter.

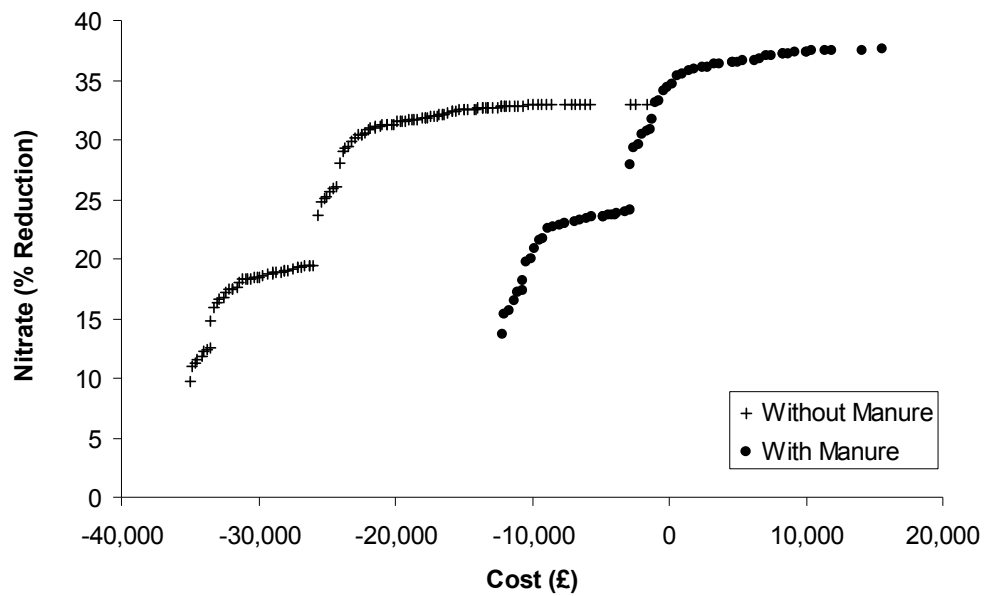


Figure 10 Variations in pareto fronts for nitrate on the Mixed combinable farm, with and without imported pig manure.

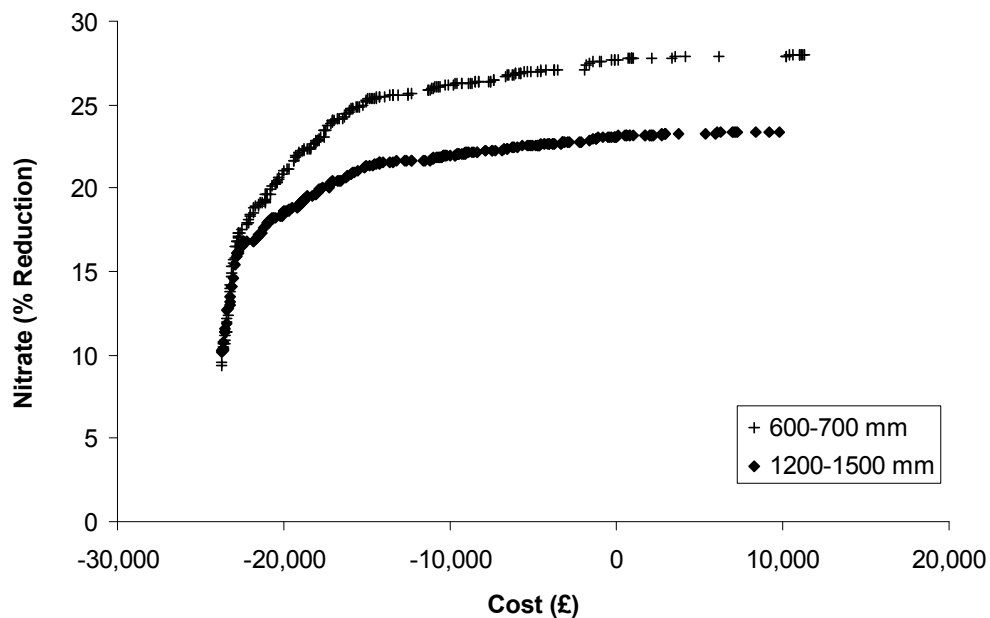


Figure 11 Pareto fronts for nitrate on Dairy farm type, for the 'impermeable – drained arable' soil type, under two different climates

The same is also true for the same farm types and climate on different soil types. Most mitigation methods tackle surface runoff and associated

phosphorus loss, than pollutant loss through preferential flow. Thus the farm on the permeable soil type, where all losses are in run off, can achieve a higher percentage reduction in pollutant loss (although the absolute reduction will be much less, as total baseline phosphorus loss is significantly smaller).

These two examples (Figure 11 and Figure 12) give some idea as to the range of reductions that can be achieved on each farm type, which should be compared with the range of reductions between farm types for one environmental set up (Table 18).

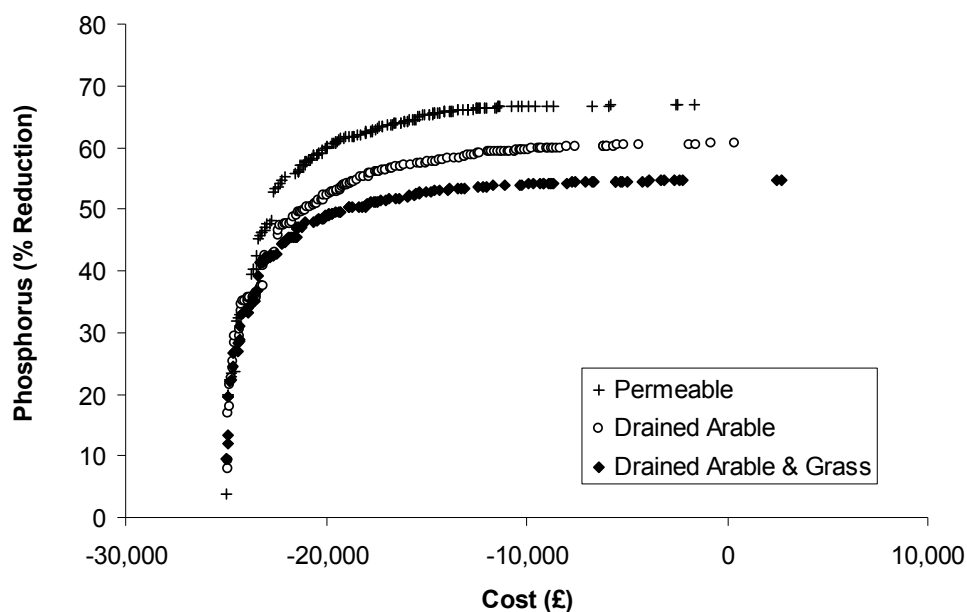


Figure 12 Pareto fronts for phosphorus on the Mixed Livestock Farm, 600-700 mm climate, on different soil types

When optimising on one pollutant only, as in the previous few examples, the mitigation methods chosen may have an impact on the losses of other pollutants, although this will not necessarily be beneficial. Figure 13 shows the changes in other pollutant losses following optimisation on phosphorus reduction.

Most of the initial methods chosen to reduce phosphorus loss at a low cost also targeted sediment loss. As more methods and / or more expensive methods were implemented, greater reductions in sediment losses could be achieved. Many of the methods targeting phosphorus loss also reduced nitrate losses, so there was a correlation between the increasing reductions achieved for phosphorus and the reductions achieved for nitrate as a by-product. Most of the combinations of methods chosen to reduce phosphorus also had a small impact on pesticide leaching, but as per nitrate and sediment, the more expensive combinations of methods had much greater impacts on pesticide losses.

For the gaseous losses, there was no such clear correlation. Most of the methods beyond the initial selection had little impact upon gaseous losses. It was only the expensive combinations of methods that achieved the greatest

phosphorus reductions that had any further effect on gaseous losses, and in the case of methane and ammonia, this may be less beneficial than the other solutions. As shown in Table 16, this increase in ammonia and methane losses was due to 'Reduce the length of the grazing day/grazing season' (Method 35), which had a considerable cost on the dairy farm for a modest decrease in phosphorus, and so was not part of the optimal solution at low cost (and thus low overall effect).

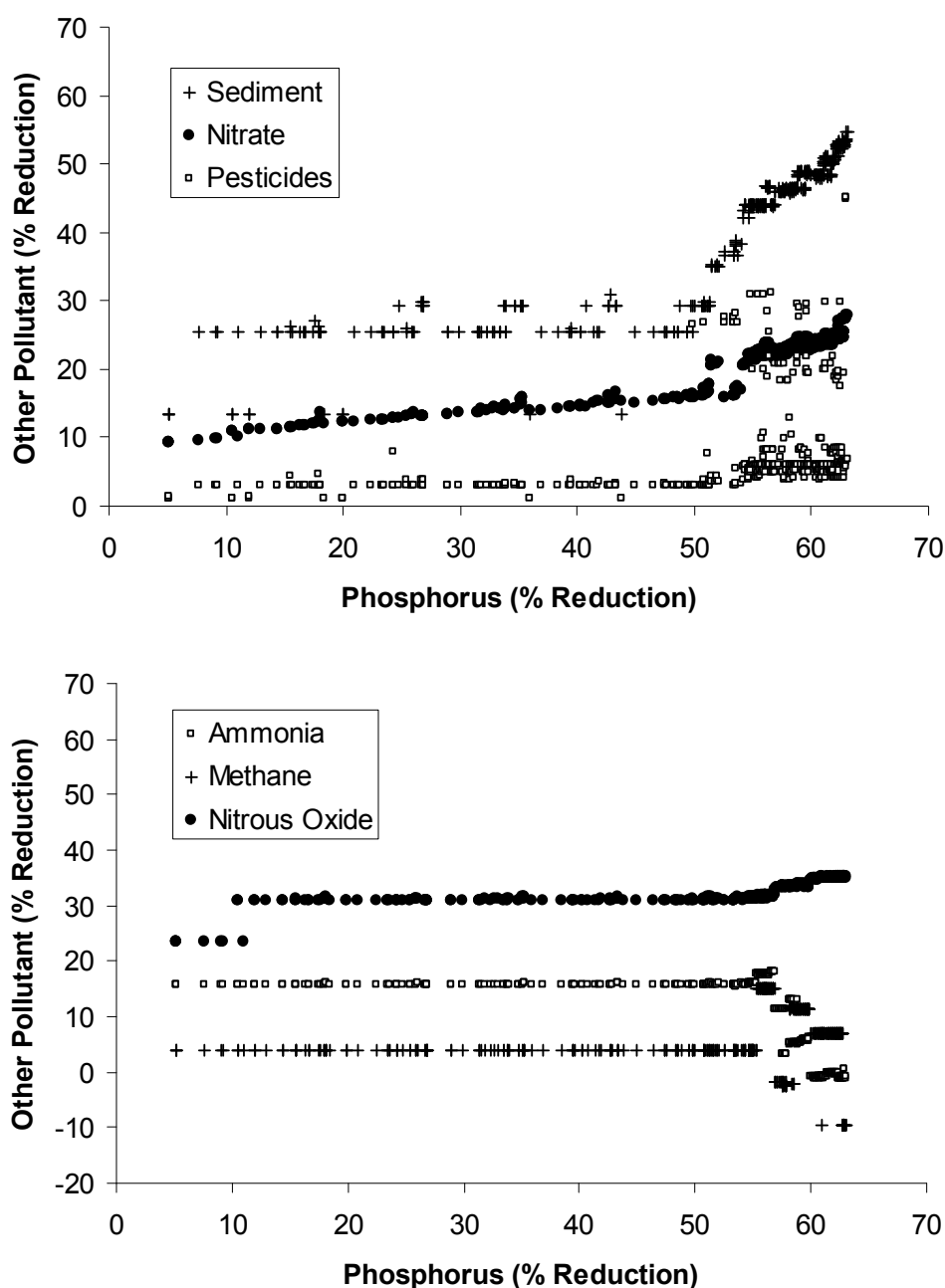


Figure 13 Reductions in other pollutants following optimisation for phosphorus mitigation on the Dairy farm.

Optimisation on one or two pollutants produced results that are relatively easy to interrogate and deduce the most desirable sets of methods as was outlined in the previous subsections. However, optimisation on multiple pollutants with many potential methods can produce a vast number of pareto-optimal solutions. Optimising on seven pollutants for the dairy farm, using 78 potential methods, produced over 20,000 unique solutions. One way to analyse these results is to sieve the data to find the cheapest sets of methods that achieve specified levels of reduction for all pollutants (Table 19). In this example, the maximum reductions were 26% for nitrate, 57% for phosphorus, 51% for sediment and ammonia, 15% for methane, 32% for nitrous oxide and 47% for pesticides. Just selecting the methods with a zero or negative cost produced reductions between 24% for nitrous oxide and 1% for pesticides for a total saving of £23,720. It was possible to achieve a minimum 15% reduction in all pollutants for a saving of £21,550. It was possible to achieve a 30% reduction in all pollutants (except for nitrate and ammonia where reductions can only reach 26% and 15% respectively) at a saving of £6,780. Before the cost of implementation becomes positive, it was possible to achieve over 40% reductions in certain pollutants.

The number of different methods required to achieve these reductions is also shown in Table 19. There are 10 methods with zero or negative cost, and these were common to all solutions. The 15% and 30% reductions mentioned previously were achieved using 17 and 44 methods respectively. A total of 55 methods were used to achieve the maximum reductions shown. However, the methods used to achieve one level of reduction were not necessarily implemented in order to achieve the higher reductions shown, for example methods 97 and 96 were selected to achieve the 5% and 10% targets, but neither of the methods were used for the 15% target. However, there is highly likely to be a solution costing just a few pounds more than the cheapest which achieves the 15% reduction, which uses a slightly different set of methods, including either method 96 or 97. Thus once an appropriate level of pollutant reduction is found, it is advisable to look at all solutions close to the point in order to select the most practical set of methods to implement.

Table 19 Effect of the minimum cost solutions that achieve minimum target pollutant reductions, for the Dairy farm type, along with the methods used to achieve the reductions.

Target (%)	Cost (£)	Nitrate	Phosphorus	Sediment	Ammonia	Methane	Nitrous Oxide	Pesticides
5	-29,913	10	6	13	16	6	24	25
10	-29,526	12	13	13	16	6	31	33
15	-28,751	16	16	36	16	6	24	40
20	-23,822	20	21	21	29	9	30	34
25	-13,418	26	55	48	31	8	30	45
30	-12,568	25	56	49	31	6	32	41
35	-12,470	25	55	49	39	6	32	41
40	-11,806	25	50	44	41	6	32	45
45	-7,474	25	52	46	57	7	32	45
50	275	26	55	52	54	8	32	45
55	1,075	26	61	50	57	8	32	45
60	8,454	27	63	52	63	8	32	45

Target (%)	Method IDs
5	96 57 41 32 31 301 300 23 22 20 19 7
10	96 95 94 92 71 57 41 32 31 301 300 25 23 22 20 19 7
15	97 96 95 92 80 74 62 57 41 32 31 300 291 27 23 22 21 20 19 13 11 9 8 7 4
20	95 94 91 81 71 64 63 57 41 36 32 31 291 290 26 25 23 22 21 20 19 16 15 14 13 11 10 4
25	97 95 94 91 83 82 81 80 79 78 71 70 63 46 41 36 33 31 32 31 291 290 27 26 25 23 22 21 20 19 16 15 14 13 11 10 9 8 7 6 5 4
30	97 96 95 92 90 83 82 81 80 79 78 74 72 71 70 62 61 57 41 32 31 300 291 27 26 25 23 22 21 20 19 16 15 14 13 11 10 9 8 7 6 5 4
35	97 96 95 92 90 83 82 81 80 79 78 74 73 71 70 57 41 32 31 301 290 25 23 22 21 20 19 16 15 14 13 11 10 9 8 7 6 5 4
40	97 95 94 91 82 81 80 79 78 74 73 71 65 64 62 57 46 41 39 38 32 31 301 300 27 26 25 23 22 21 20 19 16 15 13 9 8 7 6 5 4
45	97 95 94 92 91 81 79 78 75 74 73 72 71 64 63 61 57 46 45 41 33 31 32 31 291 27 26 25 23 22 21 20 19 16 15 14 13 11 9 8 7 6 5 4
50	97 95 94 92 91 80 79 78 75 74 73 71 62 57 56 46 44 41 39 38 37 36 33 31 32 31 291 290 27 26 25 23 22 21 20 19 16 15 14 13 11 10 9 8 7 6 5 4
55	97 95 94 92 91 80 83 82 81 80 79 78 75 74 73 72 71 70 64 62 57 45 41 39 37 36 33 31 32 31 290 25 23 22 21 20 19 16 15 14 13 10 9 8 7 6 5 4
60	97 95 94 92 91 90 83 82 81 80 79 78 75 74 73 72 71 70 69 64 63 62 61 57 46 45 44 41 39 38 37 36 33 31 32 31 291 27 26 25 23 22 21 20 19 16 15 14 13 11 10 9 8 7 6 5 4

Table 19 shows the number of methods that could be required to achieve certain levels of pollutant reduction. The same data can be presented in a different way, to show the number of methods required to achieve a proportion of the maximum potential reduction (Figure 14). To achieve the highest levels of pollutant reduction it was necessary to select upwards of 50 different mitigation methods. However, because not all methods target all pollutants, it is possible to select over 50 different methods that have a very limited effect on one or more pollutants, whereas it is possible to select just over 10 methods that can potentially achieve almost 20% of the maximum potential reduction. Note that it is not possible to achieve the maximum potential reductions in all pollutants at the same time due to 'pollution swapping' (e.g. Method 35, Table 16).

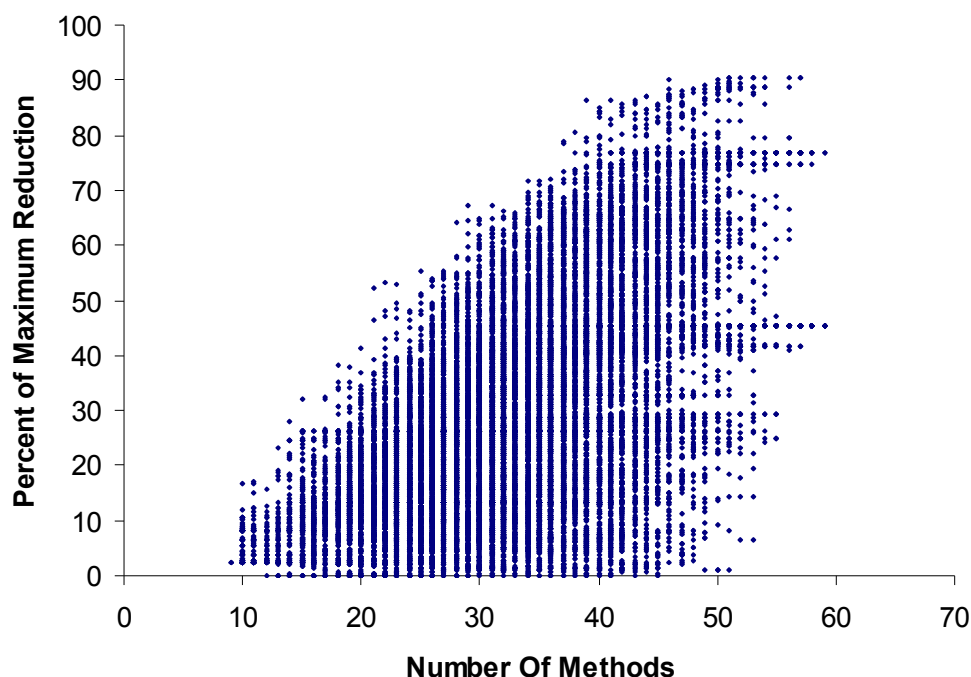


Figure 14 Number of mitigations methods required to achieve a minimum percentage of the maximum potential reduction for all pollutants.

Once an appropriate set of mitigation methods has been identified, it is important to assess the sensitivity of the pollutant reductions to the individual estimates of pollutant effectiveness and also the uncertainty in the baseline losses. Figure 15 shows the sensitivity of the pollutant reductions possible on the dairy farm used in previous examples to uncertainty in the method impacts. As stated in Section 5.3, the mean reductions in this analysis were greater than those found using the average values, as the average impact is less than the central value of the uncertainty range. Variation in reductions for nitrate, sediment, phosphorus, pesticides and nitrous oxide were all comparable in shape, and varied by between 10% and 20% of the average value. However, for methane and ammonia, where there are fewer methods in effect, there was greater sensitivity to the uncertainty in method impact, as shown by the greater slopes for these pollutants in Figure 15. It is also

important to note that the selected methods could potentially result in a net increase in methane pollution.

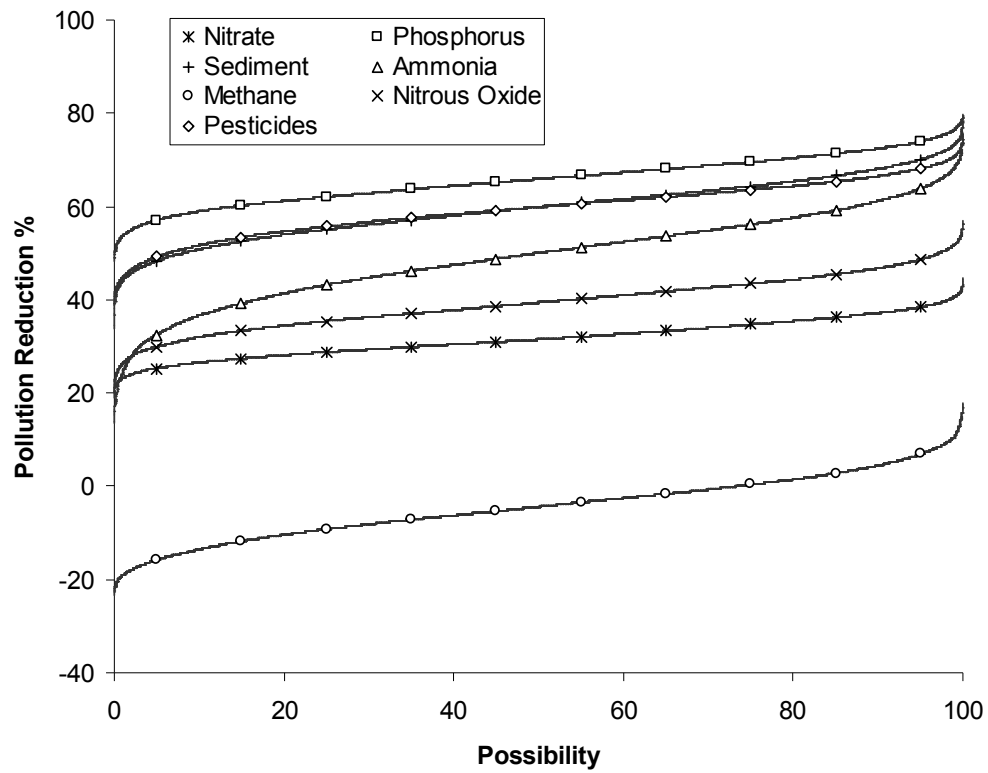


Figure 15 Sensitivity of pollutant reductions to uncertainty in method impacts.

9. Discussion and conclusions

This project has created a framework to allow the evaluation of the potential for control of diffuse agricultural emissions to air and water by a broad range of farm mitigation methods presented in Newell-Price et al. (2009) on different farm systems under different environmental conditions. The framework has been labelled as FARMSCOPER – **FARM S**cale **O**ptimisation of **P**ollutant **E**mission **R**eductions.

The descriptions of the farm systems were created under WQ0106 work package 5, and have been incorporated into FARMSCOPER to allow estimation of the pollutant losses from the different farm systems. Although these farm systems are designed to be representative of typical farms in England and Wales, FARMSCOPER allows for them to be modified by changing fertiliser and pesticide application rates, or changing the areas of cropping or livestock numbers (and thus stocking densities). Thus the system has the flexibility to allow for different farms to be created, and the impacts of suites of methods on these to be compared with the impacts on the default farms. This could be particularly beneficial in light of future agricultural changes, such as reductions in the amount of fertiliser applied, or anticipated on-going reductions in livestock numbers. Suites of mitigation methods could thus be chosen that not only reduce pollution by desired amounts on farms as they are at the moment, but that will continue to ensure sufficiently low levels of pollution in the future.

The pollutant losses were calculated using a suite of mechanistic models for the water borne pollutants and ammonia and default IPCC methodologies for nitrous oxide and methane. All of the models used have been applied in previous projects for policy support at either farm or national scale. The PSYCHIC model was used to act as a 'vector model' for all the water borne pollutants, thus ensuring a sensible commonality to sediment losses and associated particulate phosphorus and pesticide losses and to the flow pathways for the different pollutants. The pollutant models were modified where necessary to allow for a detailed apportionment of the losses between sources, areas, pathways, types, timescales and forms. This is a more detailed apportionment than has been used in previous studies and allows for a more detailed description of the impacts of mitigation methods, and thus hopefully a more accurate representation of their impacts, as it is clear exactly how the mitigation method is effective, e.g. it reduces incidental nitrate losses in runoff from dairy slurry applied to arable land, as opposed to having to estimate an overall impact on the nitrate loss, which would be required for a more simple export coefficient model. The water-borne pollutant loss models were run nationally, and the results area-weighted for a range of climate zones and soil types, such that the resultant losses were typical of the average area of England and Wales under a particular soil and climate type, rather than just for one location with a particular soil and climate.

FARMSCOPER can estimate the cost and effectiveness of mitigation methods individually, so that mitigation methods of interest can easily be identified. It also allows for the evaluation of multiple mitigation methods, as

these will not simply be the sum of the impacts of the individual methods, due to interaction and competition between methods.

FARMSCOPER includes a genetic algorithm model to search for pareto-optimal solutions for combinations of methods that reduce one or more target pollutants. Given the large number of mitigation methods available in the framework, it was necessary to use such a sophisticated approach to avoid the need to evaluate the potentially many billions of permutations of the large number of mitigation methods considered, which would be required for the cost-curve approach which has been used in previous similar studies.

FARMSCOPER allows for uncertainty in both the baseline pollutant losses and the impacts of the mitigation methods. Given targets to achieve in the levels of pollution reduction, the genetic algorithm procedure will only allow a solution to survive and propagate if it exceeds these targets in light of any uncertainty in the impacts of the suite of methods that solution represents. It is also possible to use FARMSCOPER to reveal the sensitivity of the pollutant reductions for a specified set of methods to uncertainty in baseline losses and pollutant impacts. Thus once a set of methods has been chosen, it is possible to investigate the range of impacts that a set of methods may have upon the different pollutants.

Given the wide range of results and analysis that is possible using FARMSCOPER, a comprehensive set of results is beyond the scope of this project. The results presented for a subset of potential climates and soils show that, using all available mitigation methods, reductions in pollution of over 60% could potentially be achieved for phosphorus on most farm types and close to 50% for sediment and pesticides on all farm types. The results from FARMSCOPER indicated that reductions of nitrate of up to 45%, ammonia up to 60% and nitrous oxide up to 35% were possible, but there is much greater variation with farm type. As well as the variations by farm type, some analysis was done on the impact of climate and soil type on the potential reductions. Reductions in methane are minimal on all farm types, due to the use of a method that reduced other pollutants, but increased methane losses – thus methane could be reduced further, but only at the expense of lower reductions in other pollutants. These reductions, achieved through application of all methods currently included, can result in substantial costs for a farm of up to £45,000 per annum, although efficient use of manure and fertiliser can result in savings being made on certain farm types.

For one farm type, changing soil type (but using the same climate) altered potential phosphorus reductions from 65% to 50%, although the lowest reductions were achieved on the soil type with the greatest initial phosphorus losses, and so would result in the biggest change to the total phosphorus loss. Nitrate losses under a wet climate could be reduced by a smaller fraction than losses on a dry climate, but again, there is an interaction between the reduction achieved and the initial magnitude of the nitrate loss.

The results outlined assume that all mitigation methods are implemented, but the optimisation routine allows for the trade offs between increased cost and increased reductions to be investigated and thus suitably cost-effective sets of mitigation methods can be selected.

It should be noted that the current version of FARMSCOPER is very much a first iteration or prototype of the framework. FARMSCOPER has been designed so that the detailed apportionment of the losses between sources, areas, pathways, types, timescales and forms; and the impacts and costs of mitigation methods can be updated as new information becomes available, and so that entirely new methods can be added to the current library, thus ensuring the usefulness and robustness of the framework into the future. FARMSCOPER has also been designed so that new pollutants can be readily incorporated into the system (once the baseline losses for the farm types, by climate zone and soil type, have been derived).

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