Application of the FARMSCOPER tool for assessing agricultural diffuse pollution mitigation methods across the Hampshire Avon Demonstration Test Catchment, UK

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Abstract

Agricultural diffuse pollution is a significant contributor to water and air quality in many catchments and the need to control harmful emissions remains paramount for government policy. In England, the Demonstration Test Catchments (DTCs) have been established to provide a basis for testing on-farm mitigation measures using collaborative multi-partner research and some of this work is targeting the Hampshire Avon (~1700 km\textsuperscript{2}) catchment. To help provide integrated farm advice across England and Wales, a new Excel-based tool, FARM Scale Optimisation of Pollutant Emission Reductions (FARMSCOPER), has recently been developed for characterising diffuse agricultural pollutant emissions from representative farm types and quantifying the expected impacts of control options on those losses to the environment. Against this background, this paper describes the application of FARMSCOPER in the Hampshire Avon DTC in order to assess its utility at catchment scale and the potential benefits of relevant and practical mitigation options. Spatial datasets and the Agricultural Census returns for 2009 specific to the River Avon catchment were integrated to produce a collection of representative farm types which capture the characteristics of the local physical environment, land use patterns and farm management practices. FARMSCOPER was used to estimate the annual emissions of nitrate, phosphorus, sediment, nitrous oxide, methane and ammonia for each representative farm type. The scenarios investigated comprised baseline losses with no mitigation measures implemented, current emissions using information on the present implementation of options under existing schemes and initiatives and, the maximum potential reduction possible on the basis of implementing all available and relevant options. Model outputs suggested that reductions in pollutant loads in response to the existing uptake of mitigation methods are small (e.g. 10\% for phosphorus, 7\% for sediment, 4\% for nitrate and 5\% for nitrous oxide). FARMSCOPER suggested that technically feasible pollutant reductions on the basis of the implementation of more mitigation options could be of the order of 47\% for phosphorus, 66\% for sediment, 22\% for nitrate and 16\% for nitrous oxide. This work represents the first catchment scale application of the FARMSCOPER tool.

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1. Introduction

Considerable efforts have been invested in the identification of mitigation options and the assessment of their performance in reducing agricultural diffuse pollution emissions to the environment. In many instances, previous studies have targeted specific pollutants (Bateman et al., 2007; Fezzi et al., 2010; Haygarth et al., 2009), farm types (McGechan et al., 2004; Abberton et al., 2008), or mitigation options (Collins et al., 2009a; Deasy et al., 2010). Following the introduction of overarching water policy such as the EU Water Framework Directive (WFD), there is a greater need for evidence-based quantification of the efficacy of a suite of mitigation methods on multi-pollutants which interact to influence the ecological status of freshwaters and the air quality in river catchments (Collins and McGonigle, 2008; Dawson and Smith, 2010). Furthermore, this knowledge and information has to be integrated with current economic data to help formulate cost-effective programmes of control measures (Bateman et al., 2007; Hutchins et al., 2009; Balana et al., 2011). Generic tools are therefore needed for the simple decision support frameworks required by end-users such as government agencies, water utilities and farmers (Heathwaite, 2003; Macleod et al., 2008; Hewett et al., 2009).

To help inform the management of diffuse agricultural pollution in England and Wales, an Excel-based tool named FARM Scale Optimisation of Pollutant Emission Reductions (FARMSCOPER), has recently been developed for the UK Department for Environment, Food and Rural Affairs (Defra) (Gooday and Anthony, 2010; Gooday et al., 2012). FARMSCOPER is founded on a suite of well-established models which have all been used in national-scale predictions for policy support. Parameterised with national-scale spatial input datasets, the FARMSCOPER tool is designed to produce site-specific source-apportioned pollutant losses at farm scale, to estimate the impact of single or multiple mitigation methods on the loss of agricultural pollutants to water and air and to optimise the selection of mitigation methods given targeted reduction levels for multiple pollutants. FARMSCOPER is currently being deployed to help provide integrated farm advice for diffuse pollution associated with intensive land use and management practice across England and Wales.

The Hampshire Avon catchment has recently been designated as one of the sentinel Demonstration Test Catchments (DTCs) by Defra UK to test the hypothesis that it is possible to reduce, cost-effectively, the impact of agricultural diffuse water pollution on ecological function while maintaining sustainable food production through the implementation of multiple on-farm mitigation measures. The work reported in this paper represents a contribution to the DTC programme. More specifically, the work involved the application of the FARMSCOPER tool in the Hampshire Avon DTC in order to:

- quantify multi-pollutant losses for representative farm types
- estimate the impact of the current uptake of agri-environment schemes
- explore the potential for further reductions in pollutant emissions
- assess its utility for informing catchment scale mitigation programmes.

2. Methodology

2.1. FARMSCOPER

FARMSCOPER (Gooday and Anthony, 2010; Gooday et al., 2012) was developed to predict diffuse agricultural pollution from representative farm systems associated with multiple pollutants and to determine the cost of implementation and the effectiveness of one or more mitigation methods in reducing the emissions of those multiple pollutants.

The FARMSCOPER tool is built on a suite of existing models that have been extensively applied across the UK for policy support and which are thus considered to be sufficiently robust without requiring further validation and calibration. The models are: Phosphorus and Sediment Yield Characterisation in Catchments (PSYCHIC: Collins et al., 2007; Davison et al., 2008; Stromqvist et al., 2008; Collins and Anthony, 2008; Collins et al., 2009b); National Environment Agricultural Pollution–Nitrate (NEAP-N: Anthony et al., 1996); National Ammonia Reduction Strategy Evaluation System (NARES: Webb and Misselbrook, 2004); MANure Nitrogen Evaluation Routine (MANNER: Chambers et al., 1999), and the IPCC methodology for methane and nitrous oxide (IPCC, 2006) with adjustments to the nitrous oxide calculations to account for improved representation of ammonia losses with NARES.

The PSYCHIC and NEAP-N models were applied to the whole of England and Wales at 1 km^2 resolution, and the results area-weighted to produce output for six primary rainfall zones and three soil types. The soil types were chosen to reflect pathways important for pollutant transfer: permeable free draining soils; impermeable soils where artificial drainage is required to make them suitable for arable cultivation, and; impermeable soils where artificial drainage is required to make them suitable for either arable or grassland agriculture. The gaseous pollutant models are not sensitive to local environmental conditions.

Agricultural management practice is simulated using 17 representative farm types derived from the Defra Robust Farm Type (RFT) classification scheme (Defra, 2010), which is widely adopted in existing farm surveys undertaken across England and Wales. Based on crop-specific land areas and categorised livestock data collected in the 2004 June Agricultural Census, default values were identified to describe an ‘average’ farm for each farm type across England (Defra, 2004). FARMSCOPER allows for customisation of these farm types to support more tailored application of the tool in specific catchments.

The FARMSCOPER tool contains a library of mitigation methods, each of which is characterised in terms of its impacts on the different pollutants and the costs or savings that implementation of the method would incur for farmers. Impacts of multiple mitigation methods are multiplicative, such that the effectiveness of multiple methods targeting the same aspects of pollutant loss will be less than the sum of their individual impacts. The costs of method implementation account for changes to the variable costs and gross margin of a crop or stock enterprise, changes to the fixed costs or
overheads associated with labour and machinery and capital investment. Capital costs were amortised over 5–20 years, dependent on the expected lifetime of the corresponding investment. Critically, FARMSCOPER also provides a means for optimising the selection of available mitigation methods, using a genetic algorithm approach to identifying optimal combinations of methods that reduce multiple pollutant losses. Any particular combination of mitigation methods is optimal if that is the most cost-effective way of achieving a target level of pollutant reduction. The optimisation functionality is provided using the NSGA-II genetic algorithm (Deb et al., 2001) which is widely used as a robust standard for such global search methods (Coello et al., 2007). The NSGA-II algorithm is elitist, meaning that the best solutions are preserved for each iteration, with the relative fitness of the solutions being established firstly by the Pareto front on which they lie. The algorithm, in the case of FARMSCOPER, is designed to seek solutions that minimise cost and maximise pollutant emission reduction, simultaneously. The parents of each child solution are generated by tournament selection and the diversity of solutions along the Pareto front is maintained by implementing a simple crowding operator, where solutions on the same Pareto front are given a higher probability of being selected to reproduce and survive into the next generation, if the neighbouring solutions in objective space are more distant.

2.2. The Hampshire Avon DTC

The Hampshire Avon DTC (~1700 km²) is a lowland system situated on the southern coast of England (Fig. 1). Long-term annual average rainfall ranges from 714 mm to 937 mm. Soils are primarily shallow and freely draining due to the local chalk and greensand outcrops, but deeper, seasonally waterlogged, flinty calcareous materials are present in valley bottoms. Older strata are also present, including clayey sands of the Wealden Formation and limestone of the Purbeck and Portland groups. Land use is largely rural with approximately 75% used for agriculture. Enhanced phosphorus, nitrate and sediment pressures from agricultural land are believed to have contributed to nutrient enrichment (Jarvie et al., 2005), siltation issues (Walling et al., 2008) and the occurrence of so-called ‘chalk stream malaise’ (UK Biodiversity Action Plan Steering Group for Chalk Rivers, 2004). Currently, only 24% of river length and 37% of local freshwater achieve good

Fig. 1 – The Hampshire Avon DTC.
ecological status (Dils, 2009) as defined in conjunction with the EU WFD. As a priority catchment under the England Catchment Sensitive Farming (CSF; Defra, 2012) scheme, intensive efforts are currently being made to engage farmers across the catchment through targeted one-to-one advice, clinics and capital grant funding for on-farm remedial measures. The study area also falls within a Nitrate Vulnerable Zone (NVZ) designation, as part of the UK implementation of the EU Nitrates Directive (81/676/EEC).

2.3. Generation of representative farm types for the Hampshire Avon DTC

To apply FARMSCOPER in the Hampshire Avon DTC, geo-referenced data on rainfall, soils and farm types were integrated to generate catchment-specific information on the spatial distribution of the key physical environmental parameters, land use patterns and farm management practices. The long-term rainfall record (1961–1990) at 1 km² resolution was reclassified into FARMSCOPER compatible rainfall bands. The NATMAP 1000 (national soil map of England and Wales gridded at 1 km × 1 km; LandIS, 2011) and HOST (Hydrology of Soil Types; Boorman et al., 1995) class-based rules embedded in the PSYCHIC modelling framework (Davison et al., 2008) were used to characterise soil and associated drainage status. Individual farm boundaries were based on the Rural Land Registry (RLR; Rural Payments Agency, 2009). RFT designation and the composition of land use and animal populations were derived from the returns provided by the June Agricultural Survey (JAS) in 2009 (Defra, 2009). Relevant records in JAS for each RFT were used to summarise animal numbers for each key category required by FARMSCOPER, including adult beef, adult dairy, sheep, sows and layers. Land use areas beneath grass, arable and rough grazing were also estimated from the JAS.

Based on the estimated land use and animal number information, RFTs present in the catchment were reclassified into their equivalent FARMSCOPER farm types (although results are reported in terms of RFTs since they are a more common reporting unit for policy support work in the UK). Descriptions of the FARMSCOPER farm types found in the Hampshire Avon DTC are provided in Table 1. Note that the FARMSCOPER farm types are rationalised, such that, for example, there are no livestock found on the cereal farm type and only limited cropping on the livestock farms, whereas the JAS data are statistical averages, such that, for instance, the average dairy farm in the Hampshire Avon DTC has only a few sheep. Stocking rates and cropping areas for the FARMSCOPER farm types were thus adjusted to ensure that the total livestock numbers and cropping areas reported in the Hampshire Avon were maintained during the modelled simulations. Fertiliser application rates were extracted from the 2009 British Survey of Fertiliser Practice (BSFP) (Thomas, 2010). A flow diagram summarising the key elements of data integration is presented in Fig. 2.

It is important to note that farm type information is lacking for some portions of the study catchment. GIS-based data analysis suggested that 87.3% of the catchment area is registered in the RLR database. In addition, while 1200 unique records were contained in the RLR, only 852 had corresponding survey data available from the 2009 JAS, which accounted for 78.5% of the RLR and 68.5% of the total catchment area, respectively. The mis-match between the RLR and JAS databases reflects a number of issues including the fact that

<table>
<thead>
<tr>
<th>FARMSOPER farm type</th>
<th>Defra robust farm type</th>
<th>FARMSCOPER description of the farm type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dairy</td>
<td>Dairy</td>
<td>A farm with dairy animals, some followers and a small flock of sheep. The farm has large areas of pasture and a limited area of arable land, primarily used for growing cereals and forage maize.</td>
</tr>
<tr>
<td>Lowland grazing</td>
<td>Lowland Grazing</td>
<td>The farm is a lowland beef and sheep farm. Land use is mainly grassland (two-thirds of which is cut for silage) and some arable land which is a mix of winter wheat, winter barley and forage maize.</td>
</tr>
<tr>
<td>Mixed livestock</td>
<td>Mixed</td>
<td>This farm is not dominated by any particular system, with a mixture of livestock and a reasonable area of arable land. There is a small dairy herd as well as some beef cows and followers; a small flock of sheep and a small indoor pig unit.</td>
</tr>
<tr>
<td>Mixed combinable with pig manure</td>
<td>Cereal</td>
<td>This is an arable farm, with a lot of winter cereals, but some spring cereals and legumes grown in rotation. It receives FYM and slurry from a nearby indoor pig farm.</td>
</tr>
<tr>
<td>Roots and combinable cropping with poultry manure</td>
<td>General Cropping</td>
<td>This is a mainly arable farm that receives manure from a nearby poultry farm. The arable land is used for roots crops, combinable crops and vegetables.</td>
</tr>
<tr>
<td>Horticulture</td>
<td>Horticulture</td>
<td>A mixed horticultural enterprise with no livestock and no imported manure. There are a variety of horticultural crops including cauliflowers, carrots, apples and strawberries.</td>
</tr>
<tr>
<td>Outdoor pig</td>
<td>Pig</td>
<td>This is an outdoor breeding unit, with piglets moved off the farm at one month old. The land is in a rotation of four years cereals and two years pigs. Sows are turned out onto stubbles, which becomes bare ground within a few weeks.</td>
</tr>
<tr>
<td>Specialist poultry farm</td>
<td>Poultry</td>
<td>This farm has no land for crop production. It has layers, pullets, broilers, turkeys, breeding birds and ducks. The poultry manure is sent to another farm for land spreading.</td>
</tr>
</tbody>
</table>

Table 1 – Farm type representation in the Avon DTC.
Fig. 2 – Key elements of data flow for running FARMSCOPER at catchment scale.

The former only includes those farmers who have made claims from the Rural Payment Agency. Despite such challenges in summarising the input information for FARMSCOPER, the available farm type information was considered to be sufficiently representative of the Hampshire Avon DTC as there was geo-referenced data for around 70% of the catchment in its entirety.

2.4. Scenario analysis with FARMSCOPER

Targeted management of diffuse pollution in a catchment commonly involves the need to reduce emissions from multiple sectors, and the requirement to address both water quality and greenhouse gas emissions to avoid environmental degradation and habitat loss. Using the environmental input data assembled for the Hampshire Avon DTC, FARMSCOPER was used to estimate the loadings of sediment (SS), nitrate (NO$_3$-N), phosphorus (P), ammonia (NH$_3$), methane (CH$_4$) and nitrous oxide (N$_2$O) for three different scenarios for each representative farm type:

1. ‘baseline scenario’ – baseline pollutant emissions with no mitigation measures;
2. ‘current emissions scenario’ – current pollutant losses with an estimate of the existing level of mitigation method implementation, and;
3. ‘maximum reductions scenario’ – with all the mitigation measures listed and reviewed in the Defra User Guide (Newell-Price et al., 2011) implemented to explore the maximum potential ceilings for the reductions of present day pollutant loadings.

There is a long history of farmer engagement in the Hampshire Avon catchment, driven by various national schemes and local initiatives, including the Countryside Stewardship Scheme (CSS; Natural England, 1991) and the current options as represented by the Entry and Higher Level schemes (ELS/HLS; Natural England, 2005). In addition, the study area has benefited from being designated as a priority catchment under the CSF scheme and the corresponding eligibility for capital grants for on-farm mitigation measures. The NVZ designation has also driven farm inspections for compliance, e.g. with manure storage requirements and spreading closed periods as components of the Nitrates Directive Action Programme. However, there is no information on the relative uptake of individual mitigation methods in the Hampshire Avon, so information assembled on the adoption rates of various mitigation methods for NVZ designated areas, as part of a recent national-scale assessment (Anthony et al., 2009) was used in the FARMSCOPER runs to predict the potential reductions in the estimated baseline emissions resulting from the current implementation of mitigation options. The optimisation feature within FARMSCOPER was used to assess cost-effective suites of mitigation methods that lie on the Pareto front and would be more appropriate than the implementation of all mitigation methods possible under the ‘maximum reductions scenario’.

3. Results

3.1. Summarising the key environmental settings for the Hampshire Avon DTC

Two of the rainfall categories used by the FARMSCOPER tool were identified for the study catchment, namely 700–900 mm (82% of the catchment) and 900–1200 mm (18% of the catchment). All three soil groups recognised by FARMSCOPER exist in the study area, although the catchment is dominated by permeable soils (ca. 85% of the catchment area). The JAS returns for 2009 (Fig. 3) suggested that the principal RFTs, in terms of land area occupied, in the study catchment are cereal (51%), mixed (20%), lowland grazing (11%), dairy (8%) and general cropping (5%). Other RFT categories including horticulture, pig and poultry, all represent less than 1%. About 4% is classified as ‘other’.

Table 2 summarises the combinations of FARMSCOPER farm types and associated rainfall conditions and soil drainage status for the Hampshire Avon DTC. It can be seen that cereal and mixed livestock RFTs on permeable soil are the most widespread combinations. Based on the average land area reported in the 2009 JAS survey, it was estimated that there are 292 cereal farms, 129 lowland grazing farms, 130 mixed farms, 77 dairy farms and 52 horticultural farms.

3.2. Predicted baseline multi-pollutant emissions

The predicted relative baseline pollutant loadings by RFTs can be seen in Fig. 4. It was estimated that cereal farms in the study
catchment contribute about 55% of N, 38% of P, 67% of SS and 50% of N$_2$O. Mixed farms were estimated to contribute 48% of NH$_3$, 40% of CH$_4$, and about 26% of NO$_3$-N, P and N$_2$O. The principal contribution from the dairy farm category concerned CH$_4$ emissions, with a relative contribution of 32%. These relative baseline pollutant loadings from the different RFTs are a function of the respective farm numbers in the study catchment and the predicted pollutant emissions from each.
individual farm. Therefore, to make the predicted baseline pollutant loadings more directly comparable, specific loadings were calculated to account for the varying land area represented by each farm category and the corresponding significant differences in the numbers of each RFT (Table 3). The dairy RFT was predicted to have very high specific emissions of CH₄, NO₃-N and N₂O due to the high livestock density. The highest predicted baseline-specific sediment loading was for the horticulture RFT, reflecting the presence of such farms on drained soils. The pig and poultry farms contribute less than 1% of the loads for all pollutants and so are insignificant in terms of catchment scale pollutant reductions. On this basis, these RFTs are not discussed further in this particular paper.

Higher predicted baseline scenario NO₃-N, P and SS loadings were found on the farms with higher rainfall inputs, whilst the permeable soils were predicted to have higher baseline NO₃-N loadings, but much lower P and SS loadings, compared with impermeable soils (Table 4). These results highlight the significance of field drains as an efficient delivery pathway as reported by previous work (e.g. Chapman et al., 2005; Smith et al., 2005). The predicted NH₃, CH₄ and N₂O baseline scenario loadings were the same for different rainfall conditions because FARMSCOPER uses the IPCC methodology for the estimation of greenhouse gas emissions, which is not sensitive to rainfall inputs.

FARMSCOPER also disaggregated the pollutant losses by sources, land use, and emission pathways. The typical source-apportionment results for selected pollutants for two dominant RFTs in the study catchment (cereal and mixed farms) are presented in Fig. 5. It can be seen that there are more sources responsible for producing the predicted baseline scenario diffuse pollution emissions from the mixed farm category, compared to cereal farms for which there are only one or two key sources. The average fertiliser rates on the livestock farm are lower than the combinable farm, so the contributions from N fertiliser are lower for NO₃-N, NH₃ and N₂O losses. However, total emissions for these three pollutants are all higher on the mixed farm due to the additional emissions from manure and excreta.

### 3.3. Validation of baseline scenario pollutant emissions

Data reported in Stromqvist et al., 2008 et al., suggested that between 2002 and 2004, pollutant loads in sub-catchments of the Hampshire Avon varied between 0.2 and 0.83 kg ha⁻¹ yr⁻¹.

### Table 3 – Estimated baseline scenario pollutant loadings (kg ha⁻¹ yr⁻¹) for the RFTs across the Hampshire Avon DTC.

<table>
<thead>
<tr>
<th>Robust farm type</th>
<th>NO₃-N</th>
<th>P</th>
<th>SS</th>
<th>NH₃</th>
<th>CH₄</th>
<th>N₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cereals</td>
<td>38</td>
<td>0.2</td>
<td>159</td>
<td>7</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>General cropping</td>
<td>37</td>
<td>0.1</td>
<td>117</td>
<td>7</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>Horticulture</td>
<td>34</td>
<td>0.3</td>
<td>247</td>
<td>5</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Pigs</td>
<td>42</td>
<td>0.2</td>
<td>112</td>
<td>6</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Poultry</td>
<td>0</td>
<td>0.0</td>
<td>0</td>
<td>9</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Dairy</td>
<td>40</td>
<td>0.5</td>
<td>104</td>
<td>36</td>
<td>173</td>
<td>10</td>
</tr>
<tr>
<td>Lowland grazing</td>
<td>24</td>
<td>0.4</td>
<td>80</td>
<td>15</td>
<td>98</td>
<td>7</td>
</tr>
<tr>
<td>Mixed</td>
<td>51</td>
<td>0.4</td>
<td>95</td>
<td>43</td>
<td>90</td>
<td>10</td>
</tr>
</tbody>
</table>

### Table 4 – The effects of rainfall and soil drainage status on specific scenario pollutant loadings (kg ha⁻¹) across the Hampshire Avon DTC.

<table>
<thead>
<tr>
<th>Rainfall (mm)</th>
<th>Soil drainage status</th>
<th>NO₃-N</th>
<th>P</th>
<th>SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>700–900</td>
<td>Permeable</td>
<td>34</td>
<td>0.1</td>
<td>72</td>
</tr>
<tr>
<td>700–900</td>
<td>Drained for arable</td>
<td>25</td>
<td>0.6</td>
<td>503</td>
</tr>
<tr>
<td>700–900</td>
<td>Drained for arable and grassland</td>
<td>24</td>
<td>0.8</td>
<td>507</td>
</tr>
<tr>
<td>900–1200</td>
<td>Permeable</td>
<td>36</td>
<td>0.2</td>
<td>191</td>
</tr>
<tr>
<td>900–1200</td>
<td>Drained for arable</td>
<td>31</td>
<td>1.1</td>
<td>882</td>
</tr>
<tr>
<td>900–1200</td>
<td>Drained for arable and grassland</td>
<td>27</td>
<td>1.2</td>
<td>816</td>
</tr>
</tbody>
</table>

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Figure 4 – Relative baseline pollutant loadings by RFTs across the Hampshire Avon DTC, predicted using FARMSCOPER.
for P and 25 and 125 kg ha\(^{-1}\) yr\(^{-1}\) for SS. Heywood and Walling (2003) monitored suspended sediment fluxes at four sites in the River Avon catchment and reported annual specific sediment yields between 14 and 125 kg ha\(^{-1}\) yr\(^{-1}\) for 1999. Jarvie et al. (2005) estimated that specific loadings at Knapp Mill (the overall downstream monitored outlet) from 1993 to 2000 varied between 0.57 and 0.8 kg ha\(^{-1}\) yr\(^{-1}\) for P and 10.1 and 27.9 kg ha\(^{-1}\) yr\(^{-1}\) for NO\(_3\)-N, respectively. According to FARMSCOPER, baseline scenario annual losses from agricultural land are 0.21 kg ha\(^{-1}\) yr\(^{-1}\) for P, 101 kg ha\(^{-1}\) yr\(^{-1}\) for SS, and 30 kg ha\(^{-1}\) yr\(^{-1}\) for NO\(_3\)-N, which are within the reported observed ranges for P and SS and only marginally higher for NO\(_3\)-N.

Comparison of FARMSCOPER predictions and monitored data needs to bear in mind that the tool only considers the diffuse pollutant loadings from agricultural sources, although such sources are significant in the study area. Bearing in mind the uncertainty associated with both monitored data and modelled simulations, the modelled baseline scenario emissions were considered to be acceptable.

Although it is not possible to validate the predicted gaseous emissions, they can be compared with average figures reported by the UK GHG Inventory for agriculture (Brown et al., 2012), which equate to 46 kg yr\(^{-1}\) of CH\(_4\) and 5.0 kg yr\(^{-1}\) of N\(_2\)O when expressed per hectare of agricultural land. These national average values are higher than the predicted CH\(_4\) losses of 34 kg ha\(^{-1}\) yr\(^{-1}\), but lower than the predicted 6.1 kg ha\(^{-1}\) yr\(^{-1}\) of N\(_2\)O. These differences can be attributed to the relative mix of livestock and arable farming in the Hampshire Avon DTC versus the UK as a whole.

### 3.4. Simulating the potential for mitigating ‘baseline scenario’ multi-pollutant emissions

The simulation outputs suggested that, on the assumption that the uptake rates in Anthony et al. (2009) are representative of the study catchment, existing implementation of mitigation methods has yielded varying degrees of emission reductions (Table 5) relative to the baseline scenario loadings shown in Table 3. In the case of P emissions, it can be seen that FARMSCOPER suggested that the highest reductions (>10%) have been achieved on those RFTs that have livestock (dairy, mixed, and lowland grazing). The dairy RFT also has the highest predicted reduction in baseline scenario NH\(_3\) loading. Simulated reductions for NO\(_3\)-N and SS were lower across all RFTs, with a range of 2–5% for NO\(_3\)-N and 5–9% for SS (Table 5).

It is, however, important to recognise that caution is required during the interpretation of the simulations summarised in Table 5 since the existing adoption rates for the mitigation methods rely on national averages, rather than accurate data collected specifically for the study area. More detailed, study catchment-specific information is required on the actual current uptake of mitigation measures and such data could be collected using carefully targeted farm surveys.

To establish the maximum ceilings of potential reductions in pollutant emissions on the basis of applying mitigation methods (the ‘maximum reductions scenario’), FARMSCOPER simulations were run with all available methods listed in the Defra UK User Guide (Newell-Price et al., 2011) being applied to all of the RFTs present in the study catchment. The predicted impacts on the specific loadings of different pollutants, tabulated by RFTs, are presented in Table 6. These simulations suggested that there is not much scope for further reductions in some greenhouse gas emissions (particularly CH\(_4\)) in the catchment reflecting the fact that FARMSCOPER does not consider the potential impacts of severe measures such as significant changes in livestock numbers. The results suggested that more could be achieved for phosphorus and sediment emissions using greater uptake of the preferred available mitigation methods (Table 6). FARMSCOPER simulations also suggested (Table 6) that the potential for reducing NH\(_3\) and N\(_2\)O emissions further for most of the RFTs is close to 20%. The capacity for significant reductions in the emissions of specific pollutants among the different RFTs is dependent on

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### Table 5 – The modelled impacts of the existing implementation of mitigation measures across the Hampshire Avon DTC (% reduction in the emissions of specific pollutants relative to the ‘baseline scenario’ predictions for RFTs shown in Table 3)

<table>
<thead>
<tr>
<th>Robust farm type</th>
<th>NO(_3)-N</th>
<th>P</th>
<th>SS</th>
<th>NH(_3)</th>
<th>CH(_4)</th>
<th>N(_2)O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cereals</td>
<td>4.0</td>
<td>6.0</td>
<td>7.8</td>
<td>9.0</td>
<td>0.0</td>
<td>6.2</td>
</tr>
<tr>
<td>General cropping</td>
<td>3.9</td>
<td>6.0</td>
<td>7.8</td>
<td>9.0</td>
<td>0.0</td>
<td>6.1</td>
</tr>
<tr>
<td>Horticulture</td>
<td>4.5</td>
<td>6.5</td>
<td>8.9</td>
<td>9.0</td>
<td>0.0</td>
<td>7.7</td>
</tr>
<tr>
<td>Dairy</td>
<td>4.9</td>
<td>11.6</td>
<td>4.9</td>
<td>15.2</td>
<td>10.4</td>
<td>7.6</td>
</tr>
<tr>
<td>Lowland grazing</td>
<td>2.4</td>
<td>10.4</td>
<td>4.7</td>
<td>0.3</td>
<td>0.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Mixed</td>
<td>3.0</td>
<td>14.8</td>
<td>6.3</td>
<td>4.8</td>
<td>0.3</td>
<td>5.4</td>
</tr>
</tbody>
</table>

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the characteristics of the farms. Thus, for example, the dairy farm category has the greatest potential for further reductions in N₂O emissions due to the presence of farm manures, whereas the cereal and general cropping farm types demonstrate greater potential for the abatement of SS emissions reflecting the problems of exposed soil and runoff experienced on such farms.

For the study catchment as a whole, the estimated specific pollutant loadings for the three key scenarios (baseline conditions with no implementation of measures, baseline conditions modified by the current uptake of mitigation methods and baseline conditions further modified by the implementation of all recommended methods) are summarised in Table 7.

### 3.5. Optimising the selection of mitigation measures for reducing ‘baseline scenario’ pollutant emissions

The ‘maximum reductions scenario’ described above dealt with the situation where all available mitigation methods are applied. However, there are likely to be many suites of mitigation methods which, whilst not able to achieve quite as great a reduction in pollutant emissions, are far more cost-effective. To investigate this, the optimisation feature of FARMSCOOPER was used for the two dominant farm types in the study catchment (Table 2). As the River Avon catchment is mostly within an NVZ, the optimisation feature was first used to find the optimal solutions for nitrate reductions (Fig. 6). Both the mixed and cereal RFTs could achieve NO₃-N reductions over 10% at a significant saving to the farmer. Savings were more pronounced on the livestock farm, where efficiencies in fertiliser use could be made through improved accounting for the N in manures. Reductions above 20% could be achieved, but these start to involve a net cost to the farmer, and the application of a significant number of mitigation methods. If FARMSCOOPER is used to find optimal suites of mitigation methods for both NO₃-N and SS on the mixed farm, then a more complex set of data emerges (Fig. 7). There are two groups of data in the figure, one with a lower N reduction,
which does not include cover crops as a mitigation method, and one with greater reductions that does. As more pollutants are added to the optimisation problem, more Pareto optimal suites of solutions are found – with the six pollutants optimised for the mixed farm, over 20,000 optimal combinations are found (out of the many billions of potential combinations). The cheapest combinations that achieve minimum reductions for all pollutants are shown in Table 8 (note that the cheapest combination may substantially exceed the target due to that particular combination of methods, whilst it is possible the next cheapest may only just exceed the target). Whilst still not incurring a net cost to the farmer, it is possible to achieve reduction of around 20% for NO$_3$-N and N$_2$O, and between 30 and 50% for P, SS and NH$_3$. As costs increase, the reductions for SS and P can reach 60%, although that is in comparison with the relative low baseline loading for this farm type on a permeable soil. The number of mitigation methods required to achieve the highest reductions across all pollutants is large. The nine methods selected to achieve the minimum target % reduction (Table 8) are as follows:

- do not apply P fertilisers to high P index soils
- use clover in place of grass
- integrate fertiliser and manure nutrient supply
- use a fertiliser recommendation system
- use plants with improved nitrogen use efficiency
- make use of improved genetic resources in livestock
- improved feed characterisation
- replace urea fertiliser with another form (e.g. ammonium nitrate)
- cultivate compacted tillage soils

The first six of these mitigation options are predicted to make a net financial saving for the farm due to reduced inputs. The first seven methods were found in more than two thirds of ~20,000 Pareto-optimal solutions. ‘Cultivate compacted tillage soils’ was not always selected as part of the optimal solutions due to it incurring a small cost for the farmer, whilst ‘Replacing urea fertiliser’ was not always selected as the method ‘Incorporate a urease inhibitor into urea fertiliser’ was often chosen, and these two methods are mutually exclusive. A full list of mitigation combinations for target reduction can be found in Supplementary information.

4. Conclusions

Current practice was estimated to have reduced emissions by 3–10% for all pollutants, whilst uptake of a significant number of mitigation methods could reduce emissions by a further 66% for SS, 47% for P, 22% for NO$_3$-N, 30% for NH$_3$ and 16% for N$_2$O but only 3% for CH$_4$. The limited scope for reductions in CH$_4$ emissions is because CH$_4$ emissions are largely a function of the livestock population and there are no mitigation methods that alter livestock numbers given the impact of this severe measure on farm profitability. The maximum technically feasible pollutant reductions are achieved at considerable cost, but it is possible to achieve reasonable reductions at lower cost (e.g. a cost neutral scenario on the mixed farm can achieve reductions of 20% for NO$_3$-N and N$_2$O, and between 30 and 50% for P, SS and NH$_3$). In reality, the actual selection and implementation of mitigation methods by farms reflects a number of key drivers, including amongst others, individual preferences (e.g. based on the practicality or experience of specific options) and attitudes towards technological innovation, existing knowledge transfer mechanisms, and incentives associated with agri-environment schemes and capital grant initiatives. Application of FARMSCOPER has suggested that further reduction of pollutant loadings across the Avon DTC, relative to the ‘current emissions scenario’, can be achieved with available mitigation methods. Optimised selection of mitigation methods could help to achieve significant reductions for multiple pollutants at reasonable cost.

The FARMSCOPER simulations provide a useful basis for targeting improved intervention on those farm types contributing the most to diffuse pollutant loadings. A number of challenges were experienced during the application of FARMSCOPER at catchment scale including incompleteness and inaccuracies of the 2009 JAS returns and mismatches between RLR farm geometric boundaries and corresponding JAS information. The tight prescriptions of the rationalised farm definitions in the current version of FARMSCOPER further complicated issues by necessitating the re-assignment of some JAS return information to the most relevant farm categories. Improved data availability, such as soil drainage status (an ongoing science project is seeking to update information on the presence and efficiency of field drains in

Table 8 – Effect of the minimum cost solutions that achieve minimum target pollutant reductions, for the mixed farm.

<table>
<thead>
<tr>
<th>Target reduction (%)</th>
<th>Cost (£)</th>
<th>Reduction achieved (%)</th>
<th>Number of methods</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NO$_3$-N</td>
<td>P</td>
<td>SS</td>
</tr>
<tr>
<td>5</td>
<td>–15,712</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>10</td>
<td>–14,667</td>
<td>10</td>
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<td>15</td>
<td>–13,054</td>
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<td>–7407</td>
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<tr>
<td>60</td>
<td>12,509</td>
<td>21</td>
<td>60</td>
</tr>
</tbody>
</table>
the Hampshire Avon DTC) and information on the actual uptake of mitigation methods would also improve the reliability of the modelled predictions.

In principle, and in due recognition of data accessibility issues, the same methodology for scaling up to catchment scale could be applied in most catchments across England and Wales. It is intended that the FARMSCOOPER outputs will be used to engage stakeholders across the Hampshire Avon DTC, for the ultimate purpose of helping to develop scientifically sound, economically viable and stakeholder-endorsed strategies for the improved mitigation of diffuse pollution from agriculture.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.envsci.2012.08.003.

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