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Abstract

The need to reduce agricultural pollution emissions to water and air is well documented. Designing new national policies to help combat diffuse pollution requires scenario analyses capturing key controlling factors such as the physical environment and farming systems, as well as the technically feasible impact of new on-farm mitigation scenarios. Accordingly, a new multi-pollutant modelling framework for England and Wales has been developed. This includes emissions of nitrate, phosphorus and sediment to water and ammonia, methane and nitrous oxide to air, and has been used to characterise baseline (no uptake of on-farm measures) and business-as-usual (BAU) pollutant losses, and compare these with the rates of loss under a range of new policies aimed at increasing the uptake of relevant source control measures to 95% across England and Wales. Model outputs, evaluated using national water quality monitoring data from the Environment Agency's routine monitoring programme, have been summarised at both farm (Robust Farm Type) and water management catchment (WMC) scale. Nationally, across all farm types, the median reductions in pollutant losses under the new scenarios, relative to BAU, were predicted to range between 9-16% for nitrate, 13-37% for phosphorus, 12-21% for sediment, 2-57% for methane and 10-17% for nitrous oxide. For ammonia, the range was -2-28%, indicating the potential for pollution swapping and an increase in ammonia emissions under scenarios designed to reduce nitrogen flux to waters. Increased uptake of pollution source control measures would result in a wide range of annual total (capital and operational) costs (per farm) for the major farm types, with median estimates ranging from £635 yr^{-1} (Less Favourable Areas (LFA) with grazing livestock) to £15,492 yr^{-1} (Cereals) in Nitrate Vulnerable Zone (NVZ) areas, compared with a range of £23 yr^{-1} to £13,484 yr^{-1} for the same respective farm types in non-NVZ areas. The annual total costs normalised by typical farm size would range from £6 ha^{-1} yr^{-1} (LFA with grazing livestock) to £118 ha^{-1} yr^{-1} (Mixed). The estimated median annual load reductions for all WMC's, relative to BAU, were predicted to be 16% for nitrate, 20% for phosphorus, 16% for sediment, 16% for ammonia, 15% for methane and 18% for nitrous oxide. At this scale, the corresponding median total annual costs were predicted to range up to £69 ha^{-1} yr^{-1}, with maximum estimates of >£100 ha^{-1} yr^{-1} for a quarter of the WMCs. In combination, these predictions suggest that almost perfect (95% uptake) implementation of source control measures to relevant farm systems will not deliver substantial improvements in pollutant emissions to water and air, thereby underscoring the need for additional and alternative strategies including those focussing on treatment-train approaches. The limitations of the strategic modelling exercise are also discussed.

Key words diffuse pollution; agriculture; source control; mitigation; policy; scenario analysis, uncertainty

Introduction

Diffuse water pollution from agriculture (DWPA), sometimes referred to as nonpoint source pollution) has long been recognised as a significant environmental issue at catchment, regional, national (e.g. Johnes and Burt, 1991; Johnes, 1996; Heathwaite and Johnes, 1996; Heathwaite et al., 1996; Johnes & Hodgkinson, 1998; Johnes et al., 2007; Carpenter et al., 1998; McGonigle et al., 2012; Withers et al., 2014; Zhang et al., 2014), international (e.g.

Johnes and Butterfield, 2002; Durand et al., 2011; Howarth et al., 1996) and even global (e.g. Howarth et al. 2012; Novotny, 1999; Vitousek et al., 2011) scales. Recent modelled cross-sector source apportionment for England and Wales suggested that agricultural contributions of total nitrogen, total phosphorus and sediment are dominant in 53% (63,030 km^2) of non-coastal water bodies designated for cycle two of the EU Water Framework Directive (WFD; Zhang et al., 2014). The detrimental impacts of DWPA on downstream aquatic environments have increased water treatment costs, adversely affected aquatic ecology and been detrimental to ecosystem services including those associated with recreation. Such off-site impacts of DWPA pose serious challenges for governments and environmental protection agencies in their attempts to meet the requirements prescribed by the EU WFD and daughter directives. As an example, DWPA and rural land use has been directly attributed to 28% of failures to meet WFD standards in England (Houses of Parliament, 2014) and the actual proportion which may be indirectly attributed to DWPA is much higher. In a recent paper by Greene et al. (2015) in which total N and total P flux to all UK waters, was simulated for the period 2000-2010, annual DWPA flux to waters ranged from 0.16 - 1.41 kg P/ha and from 6.56 - 29.2 kg N/ha. The % contribution from DWPA to the total flux varied from 5% P and 13% N in lowland grazed heathlands to over 76% of total P flux and 81% of total N flux to waters in more intensively farmed areas, mirroring rates reported for P flux to waters in England and Wales in an earlier study by Johnes et al. (2007).

In a bid to reduce pollutant loadings from agricultural sources, extensive research has been undertaken to design and test, individually or in combination, on-farm mitigation options which can be incorporated into existing farming practices. Field scale experiments (e.g. Deasy, et al., 2009; Stevens, et al., 2009), process-based modelling (e.g. White and Arnold, 2009), literature reviews (Collins et al., 2009a; Newell-Price, et al., 2011; Schoumans et al., 2011, 2014) and national scale scenario analysis based on farming sector reductions of N, P and sediment flux (Johnes et al., 2007; Collins et al., 2009a,b; Greene et al., 2015) have all been carried out to summarise the likely impact of mitigation measures for the agricultural sector on the rate of DWPA. As a result, some progress is being made in understanding their cost-effectiveness as well as their interactions in reducing multiple water-borne pollutant loads (including nitrogen, phosphorus, sediment), lowering emissions of green-house gases (including ammonia, methane, nitrous-oxide) and lessening impacts on the wider environment, such as delivering benefits for biodiversity and ecosystem services.

For policy support in England and Wales, the FARMSCOPER (FARM Scale Optimisation of Pollutant Emission Reduction) modelling tool has been developed for characterising diffuse agricultural pollutant emissions from representative farm types and quantifying the technically feasible impacts of on-farm control options on those losses to the environment (Zhang et al., 2012; Collins et al., 2014a; Gooday et al, 2014). This tool is built on existing models that have been extensively applied across the UK for policy support. The models are: the Phosphorus and Sediment Yield CHaracterisation In Catchments (PSYCHIC) model (Collins et al., 2007; Davison et al., 2008; Stromqvist et al., 2008; Collins and Anthony, 2008; Collins et al., 2009b,c); the National Environment Agricultural Pollution–Nitrate (NEAP-N) model (Anthony et al., 1996); the National Ammonia Reduction Strategy Evaluation System (NARSES; Webb and Misselbrook, 2004); the MANure Nitrogen Evaluation Routine (MANNER; Chambers et al., 1999), and; the IPCC methodology for methane and nitrous oxide emissions (IPCC, 2006) with adjustments to the nitrous oxide calculations to account for improved representation of ammonia losses within NARSES. Though originally designed for farm scale assessment, more recently FARMSCOPER has been extended with upscaling functions (Zhang et al., 2012; Collins et al., 2014a).

To support evidence-based strategic decision-making and the increased drive towards improved spatial targeting of mitigation measures at national scale, there is a clear need to evaluate the potential impacts of pollutant control strategies associated with different combinations of available on-farm mitigation measures. Existing work in England and Wales has been generally reported for specific pollutants including sediment, (e.g. Collins et al., 2014a) and selected priority catchments including those targeted by the Catchment Sensitive Farming (CSF) initiative (e.g. Zhang et al., 2012). Such studies have focused on assessing the technical feasibility of implementing all applicable measures and an examination of resulting variability in impacts and associated costs for different Robust Farm Types (RFTs; Defra, 2010). In recognition of the fact that it is operationally impractical and economically infeasible to apply all applicable mitigation methods at national scale, attempts have already been made to select shortlists of on-farm measures in tandem with specific policy instruments, including Cross Compliance (the minimum expectations of farmers) funded by EU Pillar I in England and Wales.

Implementing diffuse pollution controls, by definition, is challenging because DWPA is characterised by spatially and temporally variable contributing sources and so reducing these inputs by on-farm mitigation potentially involves high costs. On the basis of this challenge for remedial efforts for DWPA, it has often been argued that the best solution is to try to prevent or at least reduce the problem at source by the adoption of targeted control measures. The significance of source control has long been recognised in the source-mobilisation-delivery continuum conceptual model for diffuse pollution delivery to rivers (Lemunyon and Gilbert, 1999; Haygarth et al., 2005; Granger et al., 2010) and the recently extended nutrient transfer cascade for evaluation of the Nitrates Directive National Action Programme in Ireland (Wall et al., 2011). Source, mobilisation, pathway and delivery are also key coordinates (components) for the characterisation of on-farm mitigation measures within FARMSCOPER (Zhang et al., 2012; Gooday, 2014) thereby providing a convenient opportunity to pre-select sets of control measures for scenario analyses.

Taking into account the spatial variability of agricultural pollutant loadings and updated current on-farm mitigation for DWPA across England and Wales, this paper presents the results of application of the new national scale FARMSCOPER modelling framework to identify source control measures for the mitigation of DWPA and assess their potential efficacy and associated costs. These are reported for nutrient and sediment fluxes to water and GHG emissions, simultaneously, relative to BAU, at farm and water management catchment (WMC) scales across the whole of England and Wales.

Methods

The general approach

The general procedures for the application of FARMSCOPER at WMC scale have already been reported elsewhere (Collins, et al., 2014a). The catchment areas of the 99 WMCs vary from 77.6 km^2 to 4204.9 km^2, with a median value of 1344.5 km^2. The key elements of the modelling approach (Figure 1) can be summarised as:

1) Mapping of soil type and rainfall combinations using existing spatial data layers for England Wales. Soils have been classified into three broad groups: (i) free draining soils, (ii) soils drained for arable use, and (iii) soils drained for both arable and grassland. Annual average rainfall (AAR hereafter) has been divided into six bands (< 600 mm, 600 – 700 mm, 700 – 900 mm, 900-1200 mm, 1200-1500 mm and > 1500 mm), respectively. For each WMC (n = 99), significant soil/rainfall combinations were identified and mapped on the basis of their spatial coverage.
2) Characterisation of field management and farming activities based on the national 2010 June Agricultural Census (JAC) returns, which is still the most comprehensive data available at national scale. Cropping areas and categorised livestock numbers for each Robust Farm Type (RFT) in each WMC were used to generate typical model

farms (>5000 for England and Wales, including >700 for Wales and nearly 400 in the border areas between the two countries).

3) Parameterisation of FARMSCOPER by pairing combinations of soil group and rainfall band with the generated model RFTs, using the 2010 JAC returns.
4) Estimation of baseline (no uptake of on-farm mitigation measures) and BAU pollutant emissions to water and air using the best estimates of current cropping and livestock numbers from the 2010 JAC, as well as uptake of on-farm measures including that resulting from agri-environment schemes.
5) Evaluation of BAU pollutant emission predictions using available national scale monitoring data for multiple pollutants.
6) Estimation of the technically feasible reductions in water and air pollutant emissions, relative to BAU, on the basis of improved uptake (95% implementation rate for all source measures) of on-farm pollution source control measures.

Mapping rainfall and soil combinations

Mapping at 1 km^2 spatial resolution across England and Wales suggests that most areas have AAR between 600 - 1200 mm. This dominant range comprises three AAR bands (600 – 700 mm, 700 – 900 mm and 900 – 1200 mm) defined within FARMSCOPER with an estimated relative areal coverage of 25.7%, 30.0% and 16.5%, respectively. Other more extreme (>1200 mm) AAR bands account for <30% of the land area. The dominant soils in each 1 km^2 grid cell were grouped into three broad groups based on their respective HOST (Hydrology of Soil Types; Boorman et al., 1995) numbers: drained for arable (9, 10, 14, 18, 19, 20, 21, 22), drained for both arable and grassland (23, 24, 25) and free draining soil (others). As a proportion of agricultural soils, free draining soils are dominant at national scale, with an estimated areal coverage of 49.8%. Remaining areas are either drained for arable use (22.2%) or drained for both arable and grassland (27.9%). A multitude of rainfall and soil combinations exist, but the most significant combinations are presented in Table 3, accounting for ~80% of the land area. To capture the spatial variations in soil/rainfall combinations at WMC scale, the top two ranked combinations (by areal coverage) were identified and their land areas relative to total WMC area were estimated. Among the combinations selected on this basis, 49 WMCs have the same AAR bands, 34 have the same soil group and 16 have different AAR and soils. This suggests that the spatial variation in soils exceeds that of AAR. Free draining soils dominate in the high rainfall regions, in the western parts of England and Wales (Figure 1).

Identification of source control mitigation measures and estimation of their efficacy

There are 105 mitigation measures included in the version of FARMSCOPER (Version 3) used for this work. These include measures for reducing diffuse pollutant fluxes to water, GHG emissions, or both. The measures relate to nutrient, livestock, soil and pollutant delivery management. For this strategic modelling exercise, the built-in mitigation measures were reviewed and a subset identified (59) representing agricultural pollution source control measures (Table 1).

The efficacy of individual mitigation methods in the FARMSCOPER library is based on a number of literature reviews (e.g. Newell-Price et al., 2011) and expert judgement. The later has typically not involved structured elicitation such as application of analytical hierarchy process (AHP; Saaty, 1980), but rather, round-the-table discussion and consensus building. Given substantial gaps in the empirical evidence base for some on-farm mitigation measures and the ranges in efficacy values for the same abatement measures reported by different studies, method efficacy is summarised in FARMSCOPER on an indicator scale to provide an uncertainty range for the potential pollutant reduction impacts (Table 2). On this basis, estimates of average measure efficacy are lower than the central values of the ranges to provide a conservative assessment of impact. The predicted net impacts of multiple on-farm mitigation methods (N) are multiplicative, such that the effectiveness of combined methods will be less than the sum of their individual impacts, viz.:

$$N = 1 - \prod_{i=1}^{i=n} (1 - R_i) \qquad (1)$$

where R_i is pollutant emission reduction due to an individual on-farm mitigation measure.

The costs of mitigation measure implementation account for changes to the variable costs and gross margin of a livestock or cropping enterprise, changes to the fixed costs or overheads associated with labour and machinery and capital investment using a number of sources (e.g. Cuttle et al., 2007; Nix, 2009). Capital costs are typically amortised over 5 to 20 years, depending upon the expected lifetime of the corresponding investment and any associated loans. The simulations reported here are based on mitigation measure costs for 2013. Costs exclude those to government bodies for policy instrument administration and enforcement on the ground by agencies or catchment officers.

Update of prior implementation rates using farm survey returns and expert feedback

Within FARMSCOPER, there are default prior implementation rates for different on-farm mitigation measures under different soil types (free draining or slowly permeable), management intensity (intensive or extensive farming and specialised farming, e.g. poultry, pigs) and Nitrate Vulnerable Zone (NVZ) designation (Yes or No) which are based on farm practice surveys and expert judgement. With intense ongoing on-the-ground activities directed towards the mitigation of DWPA (e.g. via the Catchment Sensitive Farming initiative in England), the actual implementation rates evolve with time. Therefore, in order to obtain up-to-date information on prior implementation under present day BAU, targeted farm surveys have been conducted in the three main Demonstration Test Catchments (DTCs) in England: the Hampshire Avon, Wensum and Eden, to solicit farmers' current uptake and attitudes towards the mitigation measures (Newell-Price et al., 2011) listed in FARMSCOPER. The DTCs provide three representative catchments in terms of natural environment and together cover >80% of rainfall and soil combinations for England and Wales, the RFT distributions and the DWPA mitigation efforts. In total, the numbers of farms surveyed during DTC phase 1 were 38, 32 and 18 for the Hampshire Avon, Wensum and Eden catchments, respectively. Treating all farms surveyed in each DTC as one overall sample population, the uptake rate of individual mitigation measures was calculated. Summary statistics (minimum, maximum and median) of current implementation in the three DTCs were derived and then compared against the default values in the FARMSCOPER tool. Because of the limited number of farms surveyed in each catchment, only the ranges of uptake rates and their median values were examined. This data analysis suggested that current uptake rates are in broad agreement for most source control mitigation measures (43 out of 59). For those with substantial differences between the default FARMSCOPER values and the returns from the DTC phase 1 farm surveys, experts or farm advisors from the Environment Agency, local Rivers Trust and scientific community were consulted. On this basis, decisions were made to modify the default values by either adopting the DTC values, or using the average of the DTC survey and FARMSCOPER default values, depending upon the consensus view. Where there was no consensus or in depth knowledge about the uptake of specific source control measures, no changes were made to the default values. This consultation exercise resulted in the modification of prior implementation rates for 18 pollution source control measures (Table 3).

The spatial distribution of model RFTs

Based on geo-referenced JAC data for 2010, the majority of WMCs (92 out of 99) contained more than 8 RFTs, presumably because of their catchment sizes (> 1300 km^2). Most RFTs could be found in most WMCs: only LFA (less favoured area) grazing farms was restricted to a limited number (47 out of 99) of WMCs because of the corresponding designation of LFAs. The relative coverage of the different RFTs at national scale in rank order was, cereal farms (23%) > dairy farms (19%) > mixed farms (15%) > general cropping farms (13%) > LFA grazing farms (8%) > lowland grazing farms (8%). Other more specialised RFTs, including horticulture, pig farms and poultry farms, used < 15% of the land reported in the 2010 JAC. These more specialised RFTs were typically smaller than other farm types (Table 4). To represent the spatial patterns of RFTs across England and Wales, the two top ranking RFTs in terms of land area within each WMC were identified (Figure 3). There is a clear contrast between the dominance of arable farming in the east and livestock rearing in the west (Figure 3). More subtle differences were also captured in the modelling framework by using 11 unique combinations of the RFTs.

Assessment of agricultural pollution mitigation potential for the WMCs

During each FARMSCOPER run, the following estimates were generated for each individual pollutant category and model farm (n = >5000) constructed using the 2010 JAC data: total baseline pollutant loads, total modified loads resulting from the revised existing (BAU) implementation of on-farm mitigation measures (*E*) and total predicted loads (*P*) resulting from the scenario specifying increased uptake of those source control mitigation measures relevant to each RFT. To estimate the overall mitigation potential (R) for each individual (n = 99) WMC, the actual numbers of holdings for each RFT (*H*) were combined with the calculated loads (*E* and *P*) to estimate the percentage reduction resulting from the implementation of the new scenario using the equation shown below, where n is the number of RFTs modelled by FARMSCOPER:

$$R = \sum_{i=1}^{n} ((E_i - P_i) * H_i) / \sum_{i=1}^{n} E_i H_i * 100$$

For this modelling exercise, 9 RFTs were considered and the most important ones were Cereal, General cropping, Specialised pigs, Horticulture, Lowland grazing, Upland grazing, Mixed, Dairy and Specialised poultry. The JAC data reported under the remaining RFT category, 'Unclassified', were redistributed proportionally amongst the other eight RFTs where necessary.

Results and discussion

Modelled BAU agricultural pollutant emissions to water and air and their evaluation using national monitoring data

There are intrinsic pollution risks associated with the adoption of certain farming activities within a given environmental setting. FARMSCOPER accounts for spatial variability in these risks by estimating 'baseline' pollutant emissions for customised farms. These predictions do not include the uptake of any on-farm mitigation measures, reflecting instead the impact of rainfall, soils, cropping and stocking. Baseline pollutant loadings to water for nitrate, total phosphorus, sediment, and to air for ammonia, methane and nitrous oxide, were generated for the model farms created for each WMC: summary statistics reveal marked differences between the baseline pollutant emissions for the individual RFTs (Table 5). Specialised RFTs such as horticulture, specialised pigs and specialised poultry, tend to have higher pollutant loadings because of their intensive production practices, involving higher fertiliser application/feed rates and stocking densities. Even within the same RFT, substantial variation exists in baseline emissions across England and Wales because of variations in farm size and structure in terms of cropping areas, livestock type and stocking densities, driven by variations in environmental character, which in turn drive pollution mobilisation. In relative terms, the specific emissions of sediment, phosphorus and methane exhibit higher spatial variability at WMC scale, compared with those of ammonia, nitrous oxide and nitrate (Table 5).

A variety of methods can be used for model evaluation (Bennett et al., 2013). Here, evaluation of the modelled pollutant emissions to water and air were based on comparison of model estimates under the BAU scenario with monitoring data for catchments across England and Wales. FARMSCOPER is built on a suite of existing models that have been extensively applied across the UK for policy support. These model outputs, in the case of sediment and phosphorus, have previously been assessed using comparisons against field scale soil erosion rates (Collins et al., 2009b) and both catchment (Collins, et al., 2007, Stromqvist et al., 2008; Zhang et al., 2012; Comber et al., 2013) and strategic scale monitoring data (Collins et al. 2009c). Outputs from the sediment, phosphorus and nitrate models underpinning FARMSCOPER were also used for the quantification of agricultural inputs by Zhang et al. (2014) where the predicted specific loadings were compared against published PARCOM (cf. Neal and Davies, 2003 for background to PARCOM monitoring) data at national scale. It is challenging to validate the modelled BAU pollutant emissions at WMC scale because of the paucity of longer-term (minimum 10 years) observed water quality data at matching temporal and spatial scales, the confounding influence of pollutant inputs from non-agricultural sources, and differences between modelled and monitored pollutant fractions and species. Since it is widely accepted that the agricultural sector is the dominant contributor of sediment and nitrate loadings to freshwater, an updated comparison was made between the total predicted BAU agricultural loadings of sediment and nitrate for different WFD river basin districts (RBDs) and PARCOM monitoring data (1991-2010). These comparisons suggest that the modelled BAU predictions for sediment (r^2 0.59) and nitrate (r^2 0.75) are in general agreement with the PARCOM data (Figure 4), especially with respect to capturing the general relative variations in the monitored data for the RBDs. Differences between the magnitudes of the modelled and monitored data reflect a number of factors, including the modelled data representing agriculture only rather than all contributing sources (e.g. channel banks contribute significantly to sediment loads; Collins et al., 2009b,c; Zhang et al., 2014), the monitored sediment data including the organic fraction associated with suspended particulate matter (SPM; cf. Neal and Davies, 2003) which is not included in the modelling framework, and the different temporal coverage of the two datasets (2010-2013 for the modelled and 1991-2010 for the PARCOM monitoring data). In addition, the modelling framework only represents inland WFD cycle 2 water bodies, whereas the PARCOM monitoring data represent export to the near shore coastal environment. These comparisons should also bear in mind that PARCOM loads are based on routine, but infrequent, sampling which introduces bias relative to pollutant export estimates based on higher resolution sampling (Johnes, 2007a; Lloyd et al, 2015). For this reason, it is more instructive to use the PARCOM estimates for longer periods (e.g. 20 years in this study) rather than for any individual or smaller selection of years. For agricultural GHG emissions to air, a comparison was undertaken between the simulated BAU emissions of methane and nitrous oxide and the corresponding official GHG inventories from agriculture for 2013 at RBD scale (Figure 5). The comparison suggests that there is very good agreement for methane emissions (r^2 0.97) in terms of the relative differences between the RBDs, but revealed a systematic under-prediction by the national scale modelling. Comparison of modelled and measured nitrous oxide emissions (r^2 0.86) from agriculture was also reasonable in terms of the spatial patterns across the RBDs, but suggested a systematic over-prediction by the national scale modelling which was most pronounced for the Severn RBD (Figure 5).

Estimation of the potential to reduce current agricultural pollutant loads and associated annual costs at farm scale

Each on-farm source control mitigation measure has its targeted land use, field management practice and farm management routine. Its relevance and expected efficacy in the reduction of pollutant loadings for a model farm depends on farm size, composition (e.g. grass and arable area, stocking) and operations. Whilst acknowledging the uniqueness of each individual farm present in the landscape, RFT is arguably still the most recognisable typology of farms for national scale data collection and policy development in England and Wales. For each RFT, the percentage reductions in agricultural pollutant loads was modelled relative to the prior (BAU) implementation scenario (Table 6). A distinction was made between NVZ and non-NVZ areas in recognition of the potential impact of the Action Programme (AP) rules for farmers on prior implementation rates within designated areas for the Nitrate Directive. As part of the NVZ AP, farmers must adhere to specific rules for stocking, manure and manufactured fertiliser applications and minimising the risk of losses by following restrictions on the timing, location and overall rates of application. These rules can be mapped onto mitigation options (Table 1) in the modelling framework and can be summarised as follows: any person spreading nitrogen fertiliser must do so in an accurate a manner as possible (fertiliser spreader calibration in the modelling); for nitrogen all applications of organic manures and synthetic fertilisers must be planned (use a fertiliser recommendation system and integrate fertiliser and manure nutrient supply in the modelling); no person may spread manufactured fertiliser within 2 m of surface water if soils are waterlogged, flooded or snow covered or if soil has been frozen for more than 12 hours over the past 24 hours (manufactured fertiliser cannot be applied to high risk areas in the modelling). There are also closed periods for spreading of nitrogen fertiliser and no person may spread nitrogen fertiliser on land if there is a significant risk of nitrogen getting into surface water, in particular, taking into account whether the land is steeply sloping (>12°), whether there is any ground cover, the proximity of the land to surface waters, local weather conditions, soil type and the presence of land drains (avoid spreading manufactured fertiliser to fields at high risk times in the modelling framework).

Because the implementation rates of such control measures are higher in NVZs, the increased uptake of source control measures, relative to BAU, will generally have a slightly higher impact in non-NVZ areas where uptake rates of specific on-farm measures (such as the use of a fertiliser recommendation system, integration of fertiliser and manure nutrient supply, and use of fertiliser spreader calibrations) are currently lower (Table 6). The model outputs demonstrate that the increased implementation (95% implementation rate for all source control measures) of on-farm source control measures should result in the reduction of pollutant loadings from almost all RFTs (Table 6). The national median reductions in emissions from the RFTs, for example, are predicted to range between 9-16% for nitrate, 13-37 for phosphorus, 12-21% for sediment, 2-57% for methane and 10-17% for nitrous oxide. A noticeable exception is the annual ammonia loading from lowland grazing farms where the model predicts that a small increase could occur as a result of pollution swapping associated with increased uptake of source control measures relevant to livestock farming (Tables 1 and 6). The modelled outputs in Table 6 suggest that some systematic changes are predicted for some combinations of RFTs and pollutants. For nitrate and ammonia, the results suggest that greater reductions could be achieved on arable farms rather than on livestock farms, though it should be noted that the majority of nutrient fluxes from livestock farming areas occur in the form of organic N and P rather than the inorganic nitrate and ammonia fluxes simulated here

(Johnes, 2007b). For ammonia emissions, technically feasible reductions of more than 25% were predicted for cereal and general cropping farms, compared with much lower estimates for dairy, lowland grazing and LFA grazing farms (Table 6). A similar pattern, but with less contrast (>15% vs <10%) was also predicted for potential reductions in nitrate emissions associated with the increased uptake of on-farm source control measures. For phosphorus, the opposite pattern is revealed by the data summary in Table 6, with the predicted reductions for cereal and general cropping farms at 17% and 13%, compared with values of ~20% for dairy, lowland grazing and LFA grazing farms.

With respect to soil group based comparisons for the predicted impacts of increased uptake (95%) of the source control measures, significant differences are observed for technically feasible reductions in emissions to water but not to air (Table 7). This reflects the fundamental control exerted by soil type on the potential for water pollution, as opposed its more variable control on gaseous emission rates. As the results for NVZ and non-NVZ areas were similar, only those model predictions for the former are presented (Table 7). Compared with the predicted impacts for drained soils, the results in Table 7 suggest that the magnitude of reductions could be twice as high for sediment and phosphorus in areas with free draining permeable soils. The reverse trend is shown by the modelled outputs in Table 7 for nitrate load reductions with the highest reductions predicted for heavily drained soils for arable and grass.

FARMSCOPER estimates the annual capital and operational costs associated with on-farm mitigation measures separately and these are combined to calculate total costs. Monetary costs for the implementation of the selected source control measures were estimated for both NVZ and non-NVZ areas (Table 8). Negative values indicate that a saving could be made on the RFT in question. Because of the uncertainty associated with the valuation of individual on-farm measures and the volatile nature of market prices, these cost estimates should be taken as indicative of the actual costs to farms. On this basis, it is more reliable to examine the relative costs among the different RFTs. Accordingly, it is interesting to note that while capital costs will be much higher for livestock farms, given the applicability of expensive manure/slurry source control options (e.g. increase the capacity of farm slurry stored to improve timing of slurry applications; Table 1) to these enterprises, the operational costs will be much higher for arable farms given their larger size (Table 4) and corresponding increased areas covered by relevant pollutant source control options (Table 1). Generally, the increased uptake of source control measures would result in a wide range of annual capital costs to the different RFTs, with medians ranging from £136 yr^{-1} (horticulture) to £40,022 yr^{-1} (dairy) in NVZ areas and a similar range in non-NVZ areas (Table 8). The results in Table 8 suggest that small savings could be made by livestock farms in terms of operational costs (e.g. respective medians of £987 yr^{-1} and £1488 yr^{-1} in NVZ and other areas), with the increased uptake of source control measures. With regard to the total predicted annual costs associated with increased uptake of source control measures, the estimates generally higher for the major farm types, such as cereal, mixed and dairy (Table 8), reflecting their larger sizes (Table 1) and the relevance of high cost mitigation options. The main message from Table 8, therefore, is that increased uptake of source control measures would incur reasonably substantial annual costs to most farm types, in the context of reasonably low impacts in reducing pollutant emissions to water and air (Table 6).

Extrapolation to WMC scale

The estimated annual pollutant load reductions for water quality related pollutants (nitrate, phosphorus and sediment), GHG emissions (ammonia, methane and nitrous oxide) and the associated total annual costs per hectare were determined for each WMC (Figures 6, 7 and 8, respectively). For all pollutants, the median estimates of annual load reductions for all WMCs, relative to prior (BAU) implementation, ranged from 15% to 20% (Table 9). The results suggest that relatively speaking, greater reductions might be achieved for phosphorus and nitrous oxide given that many of the control measures relate to the management of organic or inorganic fertilisers (Table 1). Predicted annual reductions in sediment (Figure 6) and ammonia (Figure 7) losses exhibit the highest spatial variability among WMCs. The median total annual costs, including both capital and operational costs, are predicted to range up to £69 ha^{-1} yr^{-1} with maximum estimates of >£100 ha^{-1} yr^{-1} for a quarter of the WMCs (Table 9 and Figure 8). The mapped spatial distributions of predicted annual pollutant reductions at WMC scale, in conjunction with increased uptake of on-farm source control measures, reflect to some extent, the strong dependences between rainfall magnitude/soil type → dominant farming types → applicable source control measures → potential mitigation impacts.

Limitations

The above results should be interpreted in the context of a number of limitations and uncertainties in both the observational data and the modelling framework adopted. Farm type distribution within the rainfall/soil combinations is assumed to be random in the absence of detailed national analysis of high resolution spatial correlations. Prior (BAU) implementation rates need revisiting in terms of capturing the impact of locally-driven incentivised schemes, such as payment for ecosystem services (PES). The updated BAU implementation rates are more reflective of national policy instruments and initiatives. The administration costs of policy instruments are not included in the cost summaries which instead, reflect only the costs to farmers. A multiplicative approach to measure interaction is cautious in terms of predicting potential impacts on diffuse pollution control and locally, mitigation measures may interplay more additively, especially if they are co-designed to target specific on-farm issues such as mobilisation of pollution from a steading, transport along a track and delivery to the stream. Mitigation costs should be viewed as highly generalised on the basis of the assumption of nationally representative uniform values for the measures in the modelling framework. The costs of measure implementation can vary both spatially and temporally in response to a range of controls on market prices and operational costs including supply chain special offers (in the context of unit costs and quantity of materials required), the proximity of suppliers of raw materials and infrastructure, competition between agricultural contractors, seasonality of supply and the weather and ground conditions during installation. The current costs in the modelling framework provide values discussed and agreed with UK Government policy teams, but the potential for regional and temporal contrasts should be borne in mind. Ongoing work as part of the Demonstration Test Catchment programme is seeking to improve the cost data for those on-farm measures used most widely for diffuse pollution control across England and Wales. The modelling framework does not currently characterise baseline losses of total nitrogen (TN), nor the impact of on-farm mitigation on such losses and underestimates both fluxes from, and likely responses of these systems to, mitigation measures aimed at livestock production practices. By way of example, existing evidence suggests that 20-30% of the TN load exported to lowland permeable streams in the UK is in the form of dissolved organic nitrogen (DON), 10-20% as particulate organic nitrogen (PON), and only an average of around 50-60% as nitrate (NO_3-N) (see Johnes and Burt, 1991; Heathwaite et al., 1996; Prior and Johnes 2002; Durand et al., 2011). Hydrochemical responses to management inevitably influence both the total N flux, and the proportion of TN exported as NO_3-N, since recent evidence reviewing all full N speciation databases for European waters indicates that nitrate decreases as a proportion of TN load as TN concentration decreases (Durand et al., 2011). In upland farming systems in England and Wales, the majority of the TN load (60-80%) is reported as in the form of organic N fractions (Durand et al., 2011). Thus, to ensure that up to 80% of the TN load exported to UK waters from agriculture is not missed in any assessment of likely responses to on-farm manipulation, further work is required to capture baseline losses of the total N load and the impacts thereon of mitigation measures. Whilst nitrate typically represents the dominant component of nitrogen emissions to water from arable farming systems with high inputs of manufactured fertilisers, those with manure/slurry applications, mixed farms with livestock herds or specialist livestock, pig or poultry farms will generate nitrogen losses with higher organic fraction content. Extension of the modelling framework to include total nitrogen (cf. Johnes & Butterfield, 2002; Greene et al., 2015) would make it more consistent with the current inclusion of total phosphorus. With respect to phosphorus though, the modelling framework does not discretize emissions and impacts of mitigation thereon in terms of different phosphorus (soluble reactive P, dissolved organic P, particulate P) fractions and again, this requires further work to capture better the real contrasts between farming systems across England and Wales. These limitations for the characterisation of nitrogen and phosphorus emissions in the modelling are important in the context of existing (soluble reactive phosphorus; SRP) or potential (TN as opposed to the existing nitrate drinking water standard) targets for inland and coastal waters in the UK. Further limitations arise through a lack of detailed understanding of the response of the relevant WFD biological quality elements to reductions in DWP: incorporating predicted aquatic ecology endpoints in the models would enable a more thorough exploration of the policy options available for achieving the WFD target of "Good" ecological status. The comparisons between the modelled and measured GHG data whilst positive in terms of the relative differences between RBDs across England Wales, suggest that it would be useful to adopt the empirical data as the national pressure layers in future work.

Conclusions

A national scale framework has been used to predict the technically feasible pollutant load reductions from the agricultural sector that might be achieved with increasing (95% uptake) the uptake of on-farm source control measures in excess of their current implementation. Mitigation strategies focussing on such measures are easy to understand for farmers, in the context of the many potential sources being fixed spatially (e.g. manure/slurry stores, high risk fields due to soil type and slope) in the landscape, and help to implement a risk-averse approach to control based on the adage that prevention is better than cure. The results, however, suggest that the technically feasible pollutant reductions over BAU resulting from this mitigation scenario would be quite limited in the context of significant annual total costs to some farm types and, indeed the rates of reduction in nutrient and sediment losses predicted across all RFT. This is exacerbated by the off-site impacts of on-farm mitigation being reduced by the cross sector sources contributing pollution to waters (Collins et al., 2014b). Source control needs to be considered in the context of a treatment-train approach to diffuse pollution mitigation, targeting the different components of the pollution transfer continuum. Future work will aim to represent nutrient species and fractions more comprehensively and to convert the predicted loads and corresponding reductions into water quality (e.g. time-averaged concentrations) and aquatic ecology outcomes in order that potential benefits for the status of the freshwater environment across England and Wales can be better assessed.

Acknowledgements

The authors gratefully acknowledge the funding provided by Defra project LM0304;
Phase 2 of the Avon Demonstration Test Catchment. The DTC farm survey data were collected in conjunction with the Avon (Defra project WQ0211), Wensum (Defra

project WQ0212) and Eden (Defra project WQ02010) DTC programmes. The Environment Agency kindly provided access to national GIS layers. The authors thank the experts included in the elicitation exercise for current implementation of source control measures.

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Table 1: Pollution source control mitigation measures in the FARMSCOPER tool.

Make use of improved genetic resources in livestock
Use plants with improved nitrogen use efficiency
Fertiliser spreader calibration
Use a fertiliser recommendation system
Integrate fertiliser and manure nutrient supply
Do not apply manufactured fertiliser to high-risk areas
Avoid spreading manufactured fertiliser to fields at high-risk times
Use manufactured fertiliser placement technologies
Use nitrification inhibitors
Replace urea fertiliser to grassland with another form
Replace urea fertiliser to arable land with another form
Incorporate a urease inhibitor into urea fertilisers for grassland
Incorporate a urease inhibitor into urea fertilisers for arable land
Use clover in place of fertiliser nitrogen
Do not apply P fertilisers to high P index soils
Reduce dietary N and P intakes: Dairy
Reduce dietary N and P intakes: Pigs
Reduce dietary N and P intakes: Poultry
Adopt phase feeding of livestock
Reduce the length of the grazing day/grazing season
Extend the grazing season for cattle
Reduce field stocking rates when soils are wet
Move feeders at regular intervals
Construct troughs with concrete base
Increase scraping frequency in dairy cow cubicle housing
Additional targeted bedding for straw-bedded cattle housing
Washing down of dairy cow collecting yards
Frequent removal of slurry from beneath-slat storage in pig housing
Increase the capacity of farm slurry stores to improve timing of slurry applications
Adopt batch storage of slurry
Install covers to slurry stores
Allow cattle slurry stores to develop a natural crust
Anaerobic digestion of livestock manures
Minimise the volume of dirty water produced (sent to dirty water store)
Minimise the volume of dirty water produced (sent to slurry store)
Compost solid manure
Site solid manure heaps away from watercourses/field drains
Store solid manure heaps on an impermeable base and collect effluent
Cover solid manure stores with sheeting
Use liquid/solid manure separation techniques
Use poultry litter additives
Manure Spreader Calibration
Do not apply manure to high-risk areas
Do not spread slurry or poultry manure at high-risk times

Do not spread FYM to fields at high-risk times
Calibration of sprayer
Fill/Mix/Clean sprayer in field
Avoid PPP application at high risk timings
Drift reduction methods
PPP substitution
Construct bunded impermeable PPP filling/mixing/cleaning area
Treatment of PPP washings through disposal, activated carbon or biobeds
Plant areas of farm with wild bird seed / nectar flower mixtures
Uncropped cultivated areas
Unfertilised cereal headlands
Use dry-cleaning techniques to remove solid waste from yards prior to cleaning
Capture of dirty water in a dirty water store
Monitor and amend soil pH status for grassland
Increased use of maize silage

Table 2: Characterisation of the average efficacy of on-farm mitigation measures and corresponding uncertainty ranges.

Efficacy class	Average efficacy	Uncertainty range	Pollutant reduction
A	-	-	None
B	2	0–10	Very low
C	10	2–25	Low
D	25	10–50	Moderate
E	50	25–80	High
F	80	50–95	Very high
G	100	100	Total

Table 3: Modified prior implementation rates for the source control measures in the FARMSCOPER tool.

Mitigation method	**Default median**	**Adjusted median**
Allow cattle slurry stores to develop a natural crust	80	45
Washing down of dairy cow collecting yards	25	5
Construct troughs with concrete base	2	25
Increase the capacity of farm slurry stores to improve timing of slurry applications	1	8
Adopt phase feeding of livestock	80	15
Store solid manure heaps on an impermeable base and collect effluent	10	20
Establish tree shelter belts around livestock housing	10	20
Construct bridges for livestock crossing rivers/streams	80	25
Loosen compacted soil layers in grassland fields	10	25
Use clover in place of fertiliser nitrogen	10	30
Compost solid manure	2	20
Use plants with improved nitrogen use efficiency	0	10
Replace urea fertiliser to arable land with another form	0	25
Incorporate manure into the soil	10	45
Establish in-field grass buffer strips	2	10
Do not spread FYM to fields at high-risk times	0	35
Do not spread slurry or poultry manure at high-risk times	0	30
Use a fertiliser recommendation system	80	60

Table 3: Significant soil and rainfall (AAR) combinations across England and Wales.

Soil group and AAR (mm) combination	**%**
Free draining & 700-900 mm	13
Free draining & 900-1200 mm	10
Drained for both arable and grassland use & 700 – 900 mm	10
Drained for both arable and grassland use & 600 -700 mm	9
Drained for arable use & 600 -700 mm	8
Free draining & 600 -700 mm	8
Free draining & > 1500 mm	8
Free draining & 1200 – 1500 mm	8
Drained for arable use & 700 – 900 mm	7

Table 4: Summary size statistics for typical RTFs at WMC scale across England and Wales.

Robust Farm type (RFT)	Average area (ha)	STD (ha)	CV (%)
Cereals	138.9	58.4	42.0
General cropping	75.8	53.8	71.0
Horticulture	30.1	46.5	154.6
Specialist pig	23.9	17.7	74.3
Specialist poultry	24.6	16.1	65.6
Dairy	117.0	37.1	31.7
LFA* grazing livestock	102.3	78.2	76.5
Lowland grazing livestock	45.9	37.5	81.6
Mixed	90.3	76.3	84.5

*less favoured area

Table 5: Annual baseline pollutant emissions (kg/ha/yr) from the modelled farms in the national FARMSCOPER framework.

Pollutant	RFT	Q1*	median	Q3*	CV**
Nitrate	Cereals	24.1	33.3	44.8	62
	General cropping	5.4	13.0	25.5	155
	Horticulture	4.3	10.6	25.3	198
	Specialist pig	40.8	86.5	160.5	138
	Specialist poultry	56.7	181.9	311.7	140
	Dairy	24.7	35.3	47.7	65
	LFA grazing livestock	7.5	10.2	13.2	56
	Lowland grazing livestock	8.0	12.1	17.9	82
	Mixed	18.0	25.5	35.7	69
Phosphorus	Cereals	0.22	0.49	0.91	141
	General cropping	0.10	0.25	0.58	191
	Horticulture	0.09	0.25	0.58	198
	Specialist pig	0.34	0.94	2.30	208
	Specialist poultry	0.54	1.21	2.68	177
	Dairy	0.27	0.50	1.08	163
	LFA grazing livestock	0.12	0.25	0.54	167
	Lowland grazing livestock	0.12	0.26	0.53	161
	Mixed	0.20	0.44	0.89	159
Sediment	Cereals	110.8	264.9	526.1	157
	General cropping	54.3	154.6	362.9	200
	Horticulture	51.6	150.3	363.6	208
	Specialist pig	58.2	201.9	563.2	250
	Specialist poultry	32.4	94.3	256.6	238
	Dairy	74.2	174.5	357.2	162
	LFA grazing livestock	38.2	90.6	190.4	168
	Lowland grazing livestock	35.9	94.6	222.6	197
	Mixed	97.9	232.0	488.3	168
Ammonia	Cereals	11.4	16.1	21.5	63
	General cropping	1.4	4.3	8.8	174
	Horticulture	1.1	3.5	8.5	213
	Specialist pig	50.4	107.7	184.1	124
	Specialist poultry	85.9	277.2	357.3	98
	Dairy	29.2	41.3	47.2	44
	LFA grazing livestock	5.2	6.7	8.2	44
	Lowland grazing livestock	8.2	10.7	13.7	51
	Mixed	12.5	17.2	23.4	63
Methane	Cereals	0.6	2.3	6.0	233
	General cropping	0.0	0.3	2.8	885
	Horticulture	0.0	0.9	4.4	506
	Specialist pig	58.5	112.5	182.5	110
	Specialist poultry	32.0	58.2	93.2	105

	Dairy	139.5	208.1	236.1	46
	LFA grazing livestock	32.8	48.3	58.1	52
	Lowland grazing livestock	51.4	64.8	80.9	45
	Mixed	36.5	53.3	67.3	58
Nitrous Oxide	Cereals	4.8	6.1	7.9	50
	General cropping	2.6	4.0	7.0	110
	Horticulture	1.8	3.5	6.6	136
	Specialist pig	12.3	20.7	36.0	115
	Specialist poultry	18.5	49.8	69.4	102
	Dairy	9.6	12.0	13.5	33
	LFA grazing livestock	3.8	5.6	6.7	51
	Lowland grazing livestock	5.4	6.9	8.2	40
	Mixed	5.8	7.8	10.4	58

*Q1 and Q3 are the first and third percentiles provided by all simulated typical farms for each RFT.

** CV is an indicator of variation for any given RFT and calculated as (Q1-Q3) / median

Table 6: Modelled pollutant load reductions (%) relative to BAU implementation due to the increased uptake of source control measures by RFT. The Q1, median and Q3 estimates are based on the uncertainty ranges associated with the efficacy of the source control mitigation measures (Table 2).

Pollutant	RFT	NVZ			Other		
		Q1*	Median	Q3*	Q1*	Median	Q3*
Nitrate	Cereals	14.3	15.9	17.8	15.7	17.6	19.8
	General cropping	13.9	15.5	17.8	15.4	17.1	19.5
	Horticulture	13.9	15.4	17.7	15.2	17.2	19.3
	Specialist pig	6.3	7.5	9.8	7.0	8.4	11.1
	Specialist poultry	12.5	13.2	15.0	13.2	14.0	16.4
	Dairy	8.3	9.8	15.7	9.6	11.4	18.2
	LFA grazing livestock	7.7	9.0	11.8	8.5	9.9	12.7
	Lowland grazing livestock	8.5	9.7	15.2	9.5	10.9	16.3
	Mixed	11.4	13.0	15.8	12.9	14.7	17.9
Phosphorus	Cereals	14.7	17.3	24.3	16.5	18.9	25.0
	General cropping	10.3	13.0	15.8	11.5	14.5	16.9
	Horticulture	11.9	13.8	17.0	13.3	15.1	17.8
	Specialist pig	13.7	19.0	27.6	15.4	21.1	29.1
	Specialist poultry	32.2	36.8	45.5	35.4	39.6	47.0
	Dairy	16.5	19.6	22.5	19.2	21.3	23.7
	LFA grazing livestock	12.7	19.6	22.9	14.0	19.9	23.4
	Lowland grazing livestock	14.1	20.7	22.4	15.5	21.4	23.0
	Mixed	12.6	16.3	21.9	14.8	17.7	22.7
Sediment	Cereals	12.6	15.6	30.7	12.6	15.6	30.7
	General cropping	10.4	12.4	21.3	10.4	12.4	21.3
	Horticulture	11.2	13.7	26.4	11.2	13.7	26.4
	Specialist pig	12.0	15.8	30.7	12.0	15.8	30.7
	Specialist poultry	7.4	15.2	31.8	7.4	15.2	31.8
	Dairy	9.7	18.4	31.9	9.7	18.4	31.9
	LFA grazing livestock	5.1	19.0	24.6	5.1	19.0	24.6
	Lowland grazing livestock	7.6	21.4	32.6	7.6	21.4	32.6
	Mixed	11.1	16.6	30.8	11.1	16.6	30.8
Ammonia	Cereals	24.1	27.0	28.9	25.6	29.7	32.2
	General cropping	25.5	28.3	30.0	27.5	31.2	33.0
	Horticulture	21.0	25.3	28.4	24.2	27.5	31.1
	Specialist pig	12.9	13.8	15.1	12.9	14.0	15.4
	Specialist poultry	25.0	27.0	28.6	25.1	27.1	28.7
	Dairy	6.0	6.7	7.5	6.4	7.3	8.4
	LFA grazing livestock	-1.2	0.2	1.1	-0.6	0.4	1.7
	Lowland grazing livestock	-1.4	-0.2	0.8	-0.8	0.4	1.6
	Mixed	11.8	13.8	15.0	13.3	15.5	16.7

Methane	Cereals	1.7	2.1	8.0	1.7	2.1	8.0
	General cropping	0.0	1.7	6.2	0.0	1.7	6.2
	Horticulture	0.0	1.7	5.2	0.0	1.7	5.2
	Specialist pig	26.8	32.1	35.2	26.8	32.1	35.2
	Specialist poultry	34.5	56.5	67.4	34.5	56.5	67.4
	Dairy	17.6	18.2	18.4	17.6	18.2	18.4
	LFA grazing livestock	5.2	6.4	7.1	5.2	6.4	7.1
	Lowland grazing livestock	7.8	8.6	9.1	7.8	8.6	9.1
	Mixed	8.6	9.7	11.1	8.6	9.7	11.1
Nitrous Oxide	Cereals	16.2	16.7	17.3	18.5	19.3	20.0
	General cropping	6.5	13.5	14.9	7.7	14.7	16.5
	Horticulture	11.9	13.4	15.1	12.7	14.6	16.5
	Specialist pig	9.4	10.3	11.1	11.7	12.6	13.2
	Specialist poultry	11.8	12.4	12.7	14.2	14.7	15.0
	Dairy	14.4	14.9	15.5	16.2	16.7	17.4
	LFA grazing livestock	12.2	13.0	14.0	12.6	13.4	14.4
	Lowland grazing livestock	14.5	15.0	15.6	15.0	15.5	16.2
	Mixed	13.9	14.5	15.0	15.5	16.2	16.8

*Q1 and Q3 are the first and third percentiles provided by all simulated typical farms for each RFT.

Table 7: Modelled pollutant load reductions (%) relative to prior implementation due to the increased uptake of source control measures by soil group. The Q1, median and Q3 estimates are based on the uncertainty ranges associated with the efficacy of the source control mitigation measures (Table 2).

Pollutant	**Soil group**	**Q1***	**Median**	**Q3***
Nitrate	Free drain	8.1	11.2	13.4
	Drained for arable use	9.1	12.6	14.9
	Drained for arable and grassland use	14.9	16.9	18.6
Phosphorus	Free drain	20.3	23.1	26.2
	Drained for arable use	14.9	17.3	22.0
	Drained for arable and grassland use	11.6	13.0	15.4
Sediment	Free drain	28.7	31.1	32.3
	Drained for arable use	13.7	16.1	19.7
	Drained for arable and grassland use	6.6	9.7	11.4
Ammonia	Free drain	6.8	15.3	26.5
	Drained for arable use	6.9	15.0	26.6
	Drained for arable and grassland use	6.7	14.8	26.6
Methane	Free drain	4.9	9.1	18.7
	Drained for arable use	4.8	9.1	18.7
	Drained for arable and grassland use	4.9	9.1	18.7
Nitrous Oxide	Free drain	12.1	14.0	14.8
	Drained for arable use	12.2	14.3	15.1
	Drained for arable and grassland use	12.5	14.7	15.7

*Q1 and Q3 are the first and third percentiles provided by all simulated typical farms for each RFT.

Table 8: Estimated costs (£ yr^{-1}) for the increased uptake of source control mitigation measures by RFT.

Cost type	RFT	NVZ			Non-NVZ		
		Q1*	**Median**	**Q3***	**Q1***	**Median**	**Q3***
Capital	Cereals	862	1165	1476	862	1165	1476
	General cropping	123	313	634	123	313	635
	Horticulture	65	136	290	65	136	290
	Specialist pig	4115	8458	13850	4133	8494	13912
	Specialist poultry	405	928	1639	407	928	1640
	Dairy	27239	40022	46175	27371	40224	46395
	LFA grazing livestock	1223	1468	2046	1229	1474	2056
	Lowland grazing livestock	2257	3060	3743	2261	3066	3750
	Mixed	4543	7042	9176	4550	7056	9192
Operational	Cereals	7269	14489	19543	3635	12471	17354
	General cropping	890	3440	7801	845	3290	7363
	Horticulture	498	1570	3624	467	1494	3477
	Specialist pig	-22263	-12336	-7059	-25303	-14627	-8010
	Specialist poultry	384	2279	4146	-10419	-7919	-2948
	Dairy	-36904	-29613	-18083	-41317	-32456	-21781
	LFA grazing livestock	-1725	-987	-163	-2297	-1488	-652
	Lowland grazing livestock	-401	-150	94	-892	-582	-296
	Mixed	1317	3534	6361	496	2172	4616
Total	Cereals	8095	15492	20692	4311	13484	18704
	General cropping	950	3751	8237	906	3551	7924
	Horticulture	609	1725	3831	546	1647	3664
	Specialist pig	-7479	-4414	-2129	-10458	-6475	-3039
	Specialist poultry	766	3490	5737	-9099	-6599	-2176
	Dairy	3440	7754	12603	1339	4925	10019
	LFA grazing livestock	-155	635	1514	-673	23	1018
	Lowland grazing livestock	2260	2791	3564	1923	2371	3075
	Mixed	6736	10698	15384	5647	9092	13791

*Q1 and Q3 are the first and third percentiles provided by all simulated typical farms for each RFT.

Table 9: Estimated annual pollutant load reductions (%) and annual total costs for the increased implementation of source control mitigation measures for WMCs across England and Wales.

Summary statistics	**Nitrate %**	**Phosphorus %**	**Sediment %**	**Ammonia %**	**Methane %**	**Nitrous Oxide %**	**Total cost £**
min	10.0	15.8	9.4	3.3	6.2	13.4	-7.8
max	22.1	31.2	39.5	40.1	23.0	20.3	162.7
stdev	2.4	3.3	5.9	9.7	3.8	1.2	42.6
median	16.0	19.7	16.1	16.2	14.6	17.8	69.1
average	15.9	20.7	18.2	17.7	14.6	17.7	69.7
Q1*	14.4	18.4	14.6	9.3	13.1	17.0	35.8
Q3*	17.5	21.9	20.3	25.8	17.0	18.6	103.8

*Q1 and Q3 are the first and third percentiles provided by all simulated typical farms for each RFT.

FIGURES

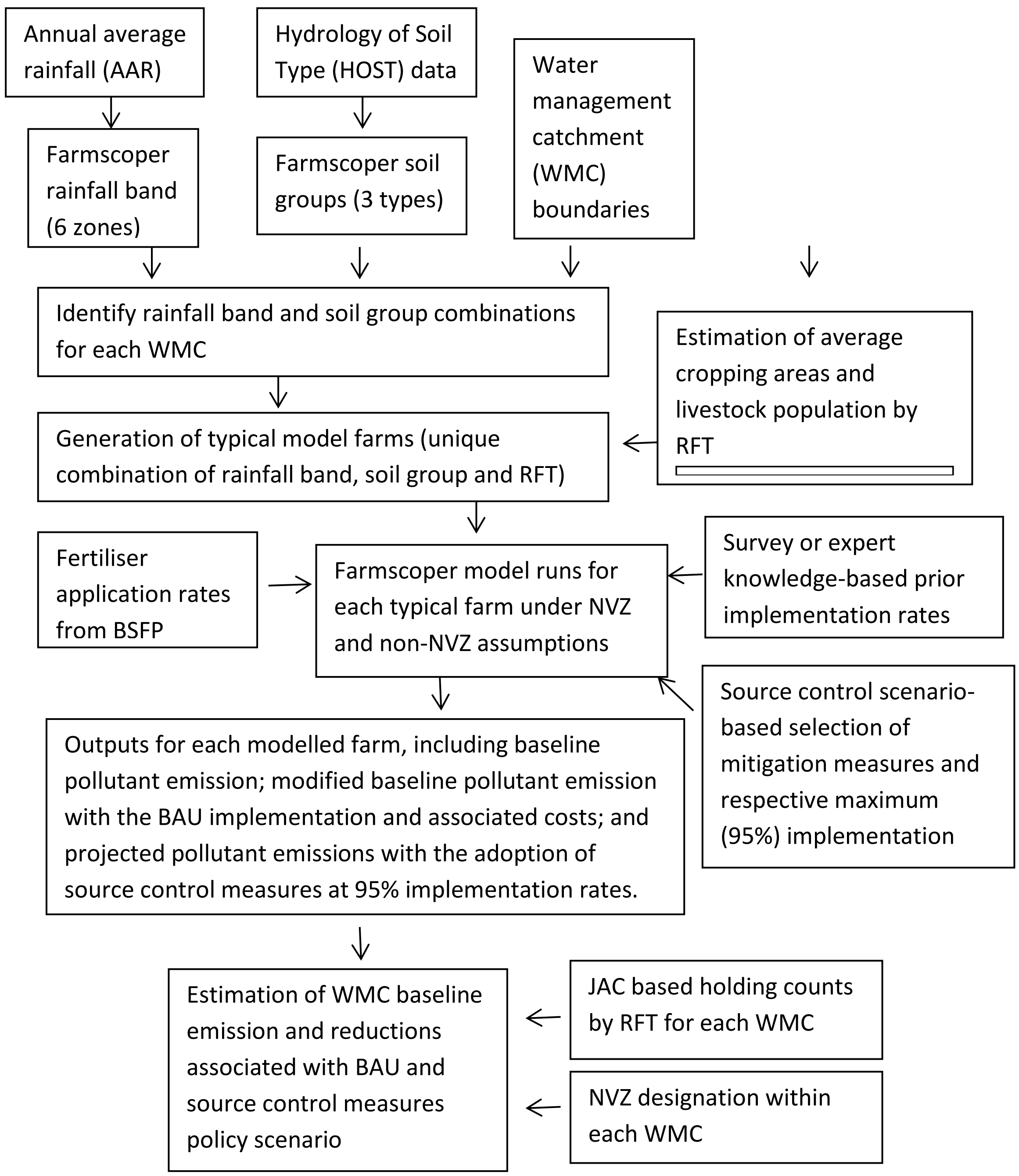


Figure 1: Key elements of data flow for running FARMSCOPER at national scale.

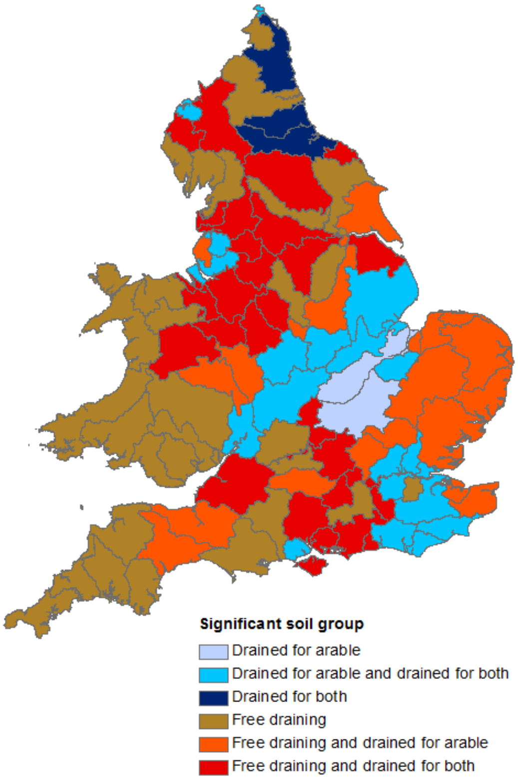


Figure 2: The spatial distribution of significant FARMSCOPER soil groups within water management catchments across England and Wales.

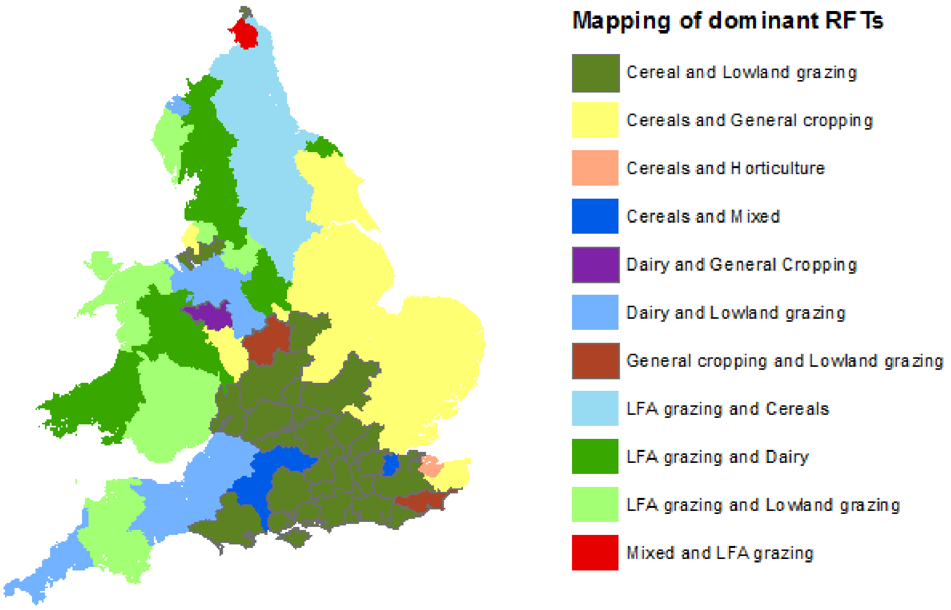
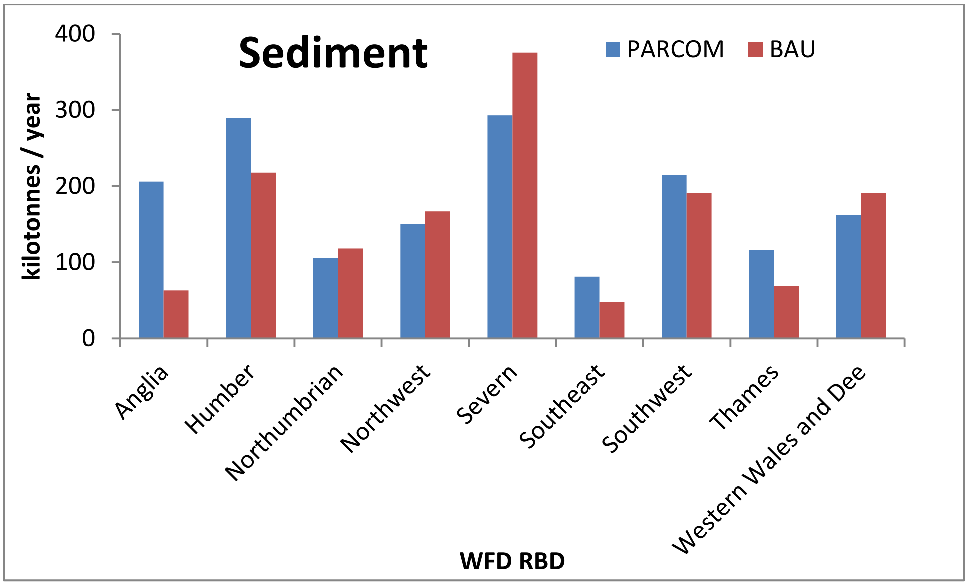


Figure 3: The spatial distribution of the dominant (by area) RFTs within water management catchments across England and Wales.



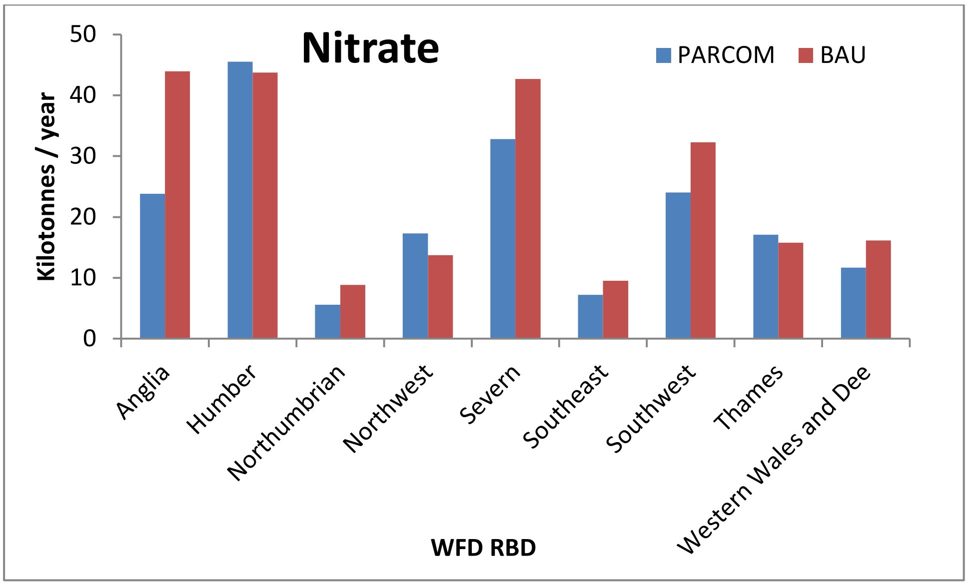
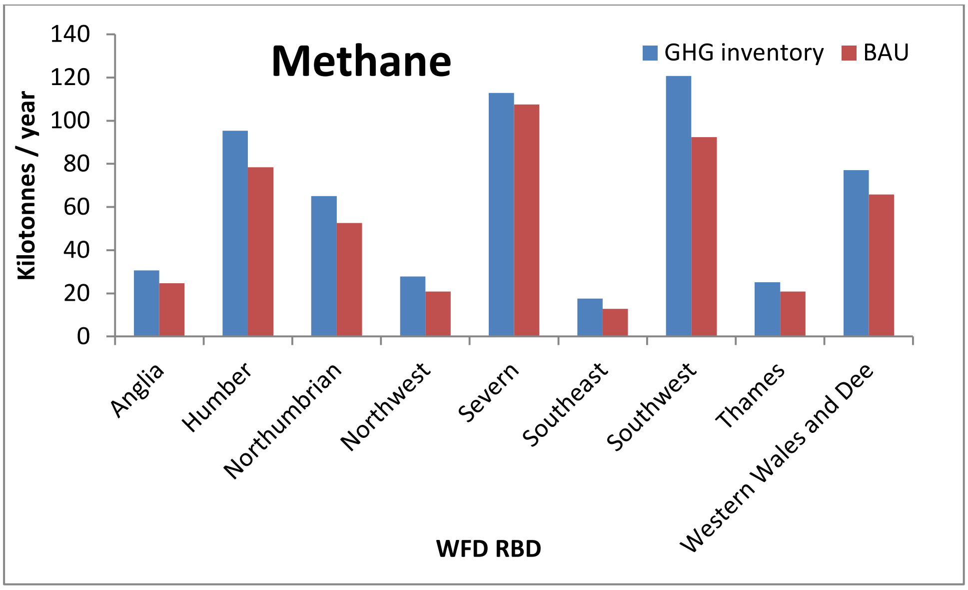


Figure 4: Comparison of modelled agricultural BAU sediment and nitrate emissions to water with PARCOM (1991-2010) monitoring data at WFD RBD scale.



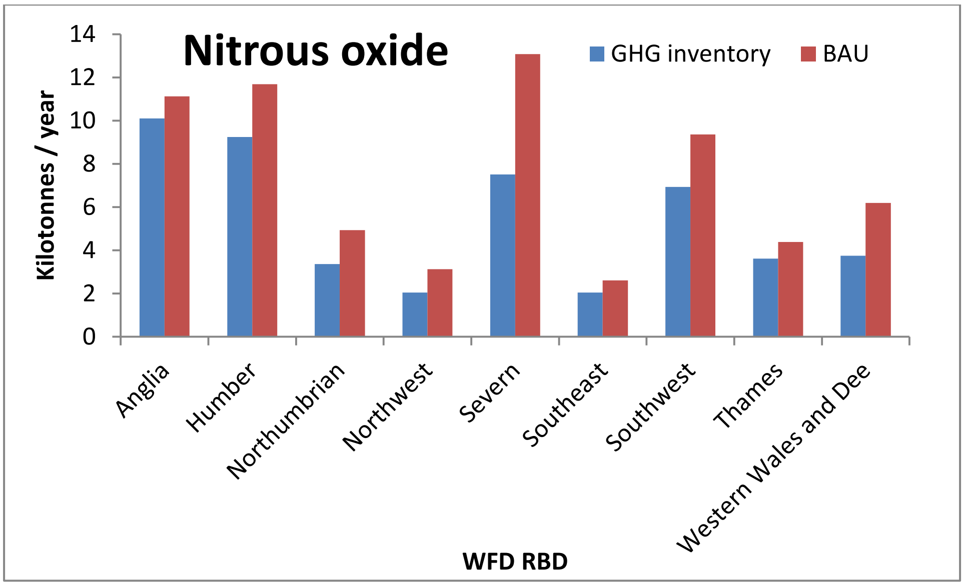


Figure 5: Comparison of modelled agricultural BAU GHG emissions to air with published GHG inventory (2013) data at WFD RBD scale.

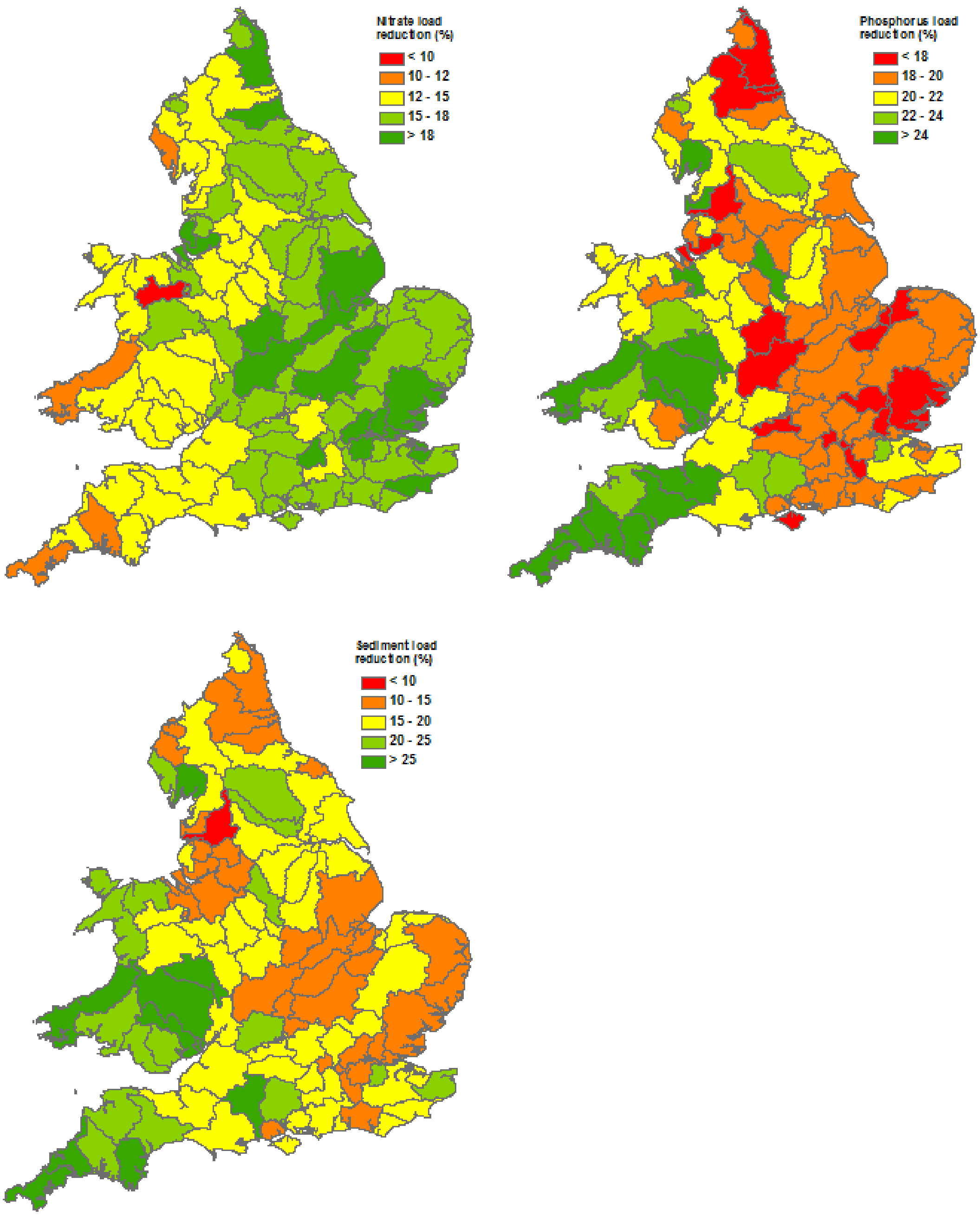


Figure 6: Estimated annual load reductions (% relative to BAU) for water quality related pollutants at WMC scale across England and Wales.

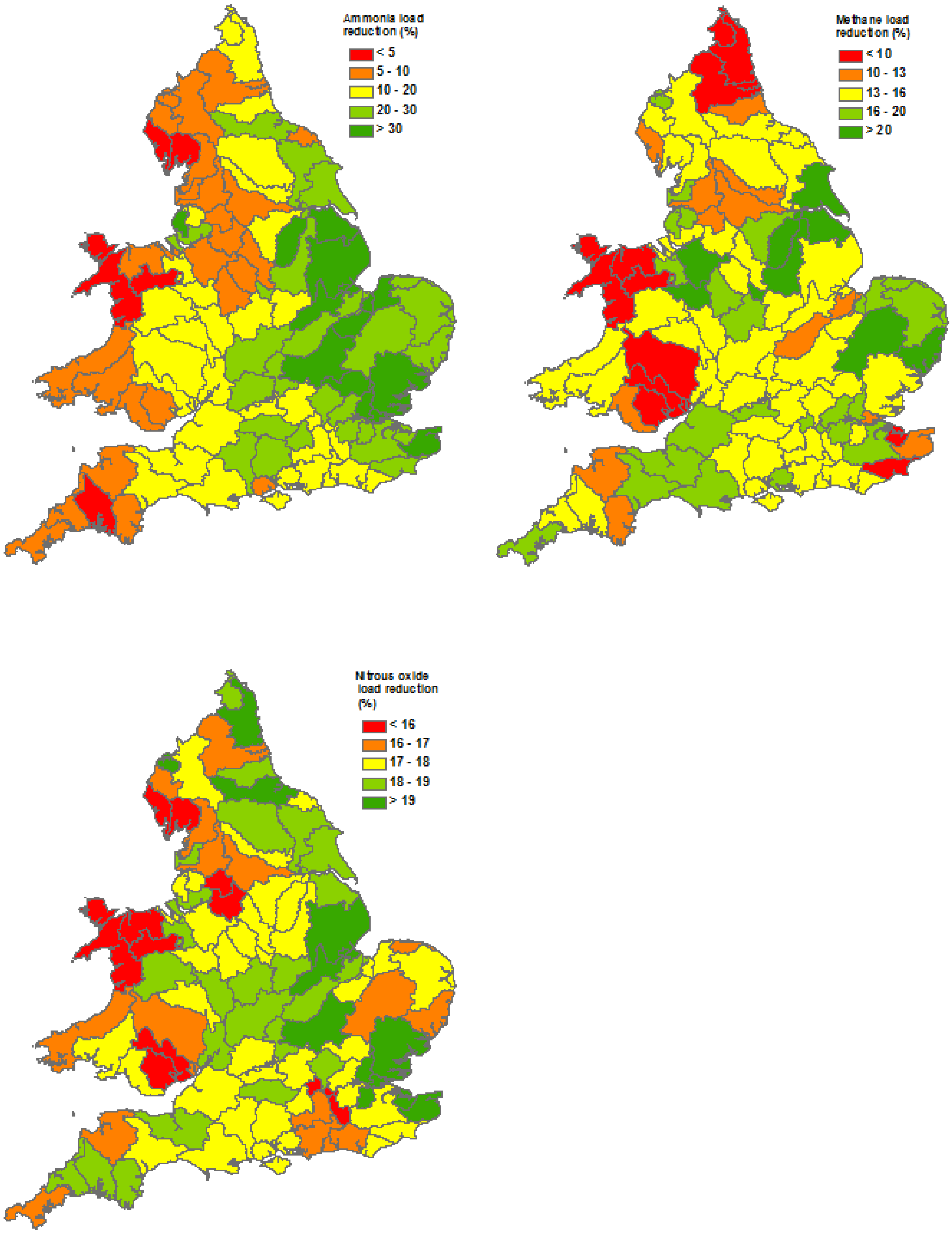


Figure 7: Estimated annual GHG emission reductions (% relative to BAU) at WMC scale across England and Wales.

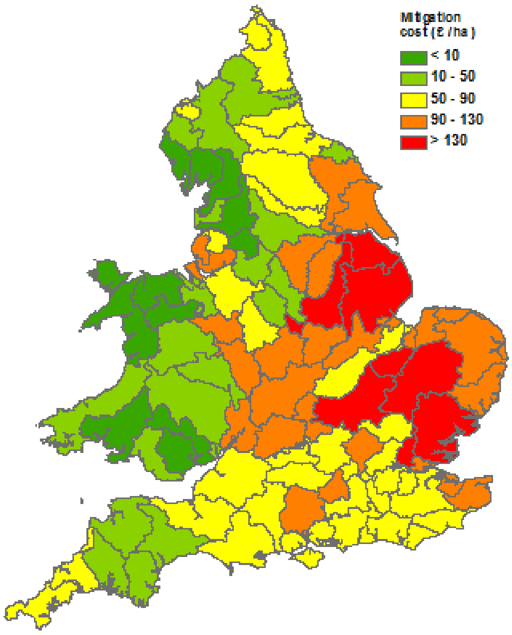


Figure 8: Estimated annual total costs for the increased implementation of source control measures at WMC scale.