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Tackling agricultural diffuse pollution: what might uptake of farmer-preferred measures deliver for emissions to water and air?

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Abstract

Mitigation of agricultural diffuse pollution poses a significant policy challenge across Europe and particularly in the UK. Existing combined regulatory and voluntary approaches applied in the UK continue to fail to deliver the necessary environmental outcomes for a variety of reasons including failure to achieve high adoption rates. It is therefore logical to identify specific on-farm mitigation measures towards which farmers express positive attitudes for higher future uptake rates. Accordingly, a farmer attitudinal survey was undertaken during phase one of the Demonstration Test Catchment programme in England to understand those measures towards which surveyed farmers are most receptive to increasing implementation in the future. A total of 29 on-farm measures were shortlisted by this baseline farm survey. This shortlist comprised many low cost or cost-neutral measures suggesting that costs continue to represent a principal selection criterion for many farmers. The 29 measures were mapped onto relevant major farm types and input, assuming 95% uptake, to a national scale multi-pollutant modelling framework to predict the technically feasible impact on annual agricultural emissions to water and air, relative to business as usual. Simulated median emission reductions, relative to current practise, for water management catchments across England and Wales, were estimated to be in the order sediment (20%) > ammonia (16%) > total phosphorus (15%) > > nitrate / methane (11%) > nitrous oxide (7%). The corresponding median annual total cost of the modelled scenario to farmers was £3 ha^{-1} yr^{-1}, with a corresponding range of -£84 ha^{-1} yr^{-1} (i.e. a net saving) to £33 ha^{-1} yr^{-1}. The results suggest that those mitigation measures which surveyed farmers are most inclined to implement in the future would improve the environmental performance of agriculture in England and Wales at minimum to low cost per hectare.

Key words

agricultural pollution; mitigation; farmer attitudes; multi-pollutant modelling; uncertainty

Introduction

Controlling excessive emissions of diffuse pollutants to water and air continues to represent a major policy challenge in many countries. Given the important role of agriculture in contributing to such diffuse pollution problems in the UK and elsewhere (Johnes and Hodgkinson, 1998; Johnes et al., 2007; Sutton et al., 2011; Zhang et al., 2014; Greene et al., 2015), farmers must be seen as key agents in delivering improved environmental solutions, especially as agricultural environmental regulation commonly fails to deliver desired outcomes (Doole et al., 2013). Over the past two decades, the expectations of farming have changed in that farmers are no longer simply expected to deliver food for a growing population but, in addition, to protect and enhance environmental goods and services such as biodiversity, amenities and water and air quality (OECD, 2013). During the 1970's and 1980's, delivery of information on best farming practices focussed on traditional knowledge transfer extension approaches on the assumption that knowledge and innovation originate solely from science which is subsequently transferred to farmers (Rogers, 1983; Black, 2000). Over time, however, innovation transfer from science to farmer has been increasingly criticised in the context of farmers' capability to generate their own knowledge and action plans for combating diffuse pollution (Chambers et al., 1989; Buttel, 2001). Hence, an alternative paradigm has emerged recognising human development principles of participation, empowerment and co-ownership of the 'wicked' problem of agricultural diffuse pollution (Black, 2000). This alternative paradigm sees farmers and scientists co-working to develop pathways for improving sustainability.

Understanding farmer receptiveness and attitudes towards on-farm diffuse pollution mitigation options is critical to developing an inclusive approach to controlling the detrimental impact of farming on environmental quality (Blackstock et al., 2010; Buckley, 2012). Existing work has identified a number of key factors influencing farmer decision-making and participation in environmental schemes including, social capital (Wilson and Hart, 2000), financial constraints (Cary and Wilkinson, 1997) and the degree of practicality involved (Saltier et al., 1994). Besides formal schemes, both catchment management and agricultural social science literature increasingly recognise the need for voluntary action by farmers in the context of environmental regulation and government subsidies (Sabatier et al., 2005; Blackstock et al., 2010). Given transgressions and associated enforcement and compliance monitoring costs for environmental regulations, policymakers have increasingly sought farmer consultation in policy design to help limit non-compliance problems (May and Winter, 1999, 2001; Davies and Hodge, 2006; Taylor et al., 2013).

The Demonstration Test Catchment (DTC) programme (McGonigle et al., 2014) was initiated in December 2009 in response to the ongoing need to characterise rural diffuse pollution problems and assemble evidence on the efficacy of suites of on-farm mitigation measures at landscape scale. This platform has a strong focus on the monitoring of pollutant emissions and aquatic ecology at landscape scale, comparing control and manipulated sub-catchments pre- and post-intervention and the programme has also involved a baseline farm business survey in the core monitored landscapes to gather data on farm business structures (e.g. cropping, livestock numbers, tillage practices) and levels of profitability. The baseline farm survey was also used to gather information from farmers in the DTCs on their current uptake of on-farm mitigation measures for controlling diffuse pollution and more importantly, their preferences for the future. Against this background, this contribution reports the findings of the baseline farm survey on farmer preferences for future uptake of diffuse pollution control measures. It combines these survey returns with a national scale multi-pollutant modelling framework to assess the potential additional benefits**,** with uncertainty ranges, of increased (95%) implementation of measures most acceptable to farmers for the control of pollutant emissions to water and air, relative to those generated by business-as-usual (BAU).

Approach

The DTC baseline farm survey

A baseline survey was undertaken in the three main DTCs (Hampshire Avon, Eden and Wensum; Figure 1) between February 2012 and February 2013. This baseline survey comprised a structured questionnaire on farmer attitudes towards the future uptake of 86 diffuse pollution mitigation measures detailed in the version of the Defra User Guide (Newell-Price et al., 2011) available at that time. As well as being asked whether they would be ‘very likely’, ‘likely’, or ‘would never consider doing particular mitigation measures in the future’, farmers were also asked to prioritise their top three measures for future uptake. In the Avon DTC, the questionnaire was posted to the sample and farmers requested to selfcomplete (n = 23), whereas face-to-face interviews were conducted in the Eden (n = 18) and Wensum (n = 32) DTCs after initial telephone contact. The Avon responses were quality assured by an experienced farm advisor given that these returns were completed by farmers. All farmers were given the choice to opt out. The baseline survey was managed by local DTC staff (e.g. farm advisors, Rivers Trust staff) with track records in engaging and working with farmers.

National scale modelling of agricultural emissions to water and air

The national modelling framework uses FARMSCOPER (FARM SCale Optimisation of Pollutant Emission Reductions; Zhang et al., 2012; Gooday et al., 2014; Collins et al., 2014) which combines a suite of well-established policy support models to simulate sediment, phosphorus and nitrate emissions to water and ammonia, methane and nitrous oxide emissions to air. The combination of pollutant pressure layers in FARMSCOPER means that the technically feasible impact of mitigation scenarios can be simultaneously predicted for multiple pollutants thereby accounting for potential pollution swapping. For sediment, FARMSCOPER uses the PSYCHIC (Phosphorus and Sediment Yield CHaracterisation In Catchments) model (Collins et al., 2007, 2008; Davison et al., 2008; Collins and Anthony, 2008; Stromqvist et al., 2008; Collins et al., 2009a,b; Comber et al., 2013). Nitrate losses are estimated, using the same hydrological framework as PSYCHIC, by disaggregating lumped coefficients from the NEAP-N (Lord and Anthony, 2000; Silgram et al., 2001) model using N-CYCLE (Scholefield et al., 1991), NITCAT (Lord, 1992), MANNER (MANure Nutrient Evaluation Routine; Chambers et al., 1999) and EDEN (Gooday et al., 2008) all of which are sensitive to soil hydrology, cropping history, fertiliser and manure nitrogen inputs and crop off-take and stocking. Ammonia emissions in FARMSCOPER are estimated for each stage (housing, storage and spreading) using the

NARSES (National Ammonia Reduction Strategy Evaluation System; Webb and Misselbrook, 2004) and MANNER models. Ammonia emissions from nitrogen fertiliser are calculated using the NT26AE model (Chadwick et al., 2005). Methane emissions are based on the IPCC (2006) methodology, using default coefficients derived for Western Europe (Baggott et al., 2006). Direct and indirect nitrous oxide emissions from fertiliser, excreta and managed manures are also calculated according to the IPCC methodology. FARMSCOPER estimates area-weighted average pollutant emissions to water and air for key soil and climate zones across England and Wales (Table 1). The soil types reflect the likelihood of agricultural under-drainage: permeable free draining soils; impermeable soils where artificial drainage is required for arable cultivation, and; impermeable soils where artificial drainage is required for either arable or grassland agriculture. NATMAP1000 (National Soil Resources Institute, Cranfield University) is used to identify soil types for each 1 km^2 grid cell at national scale and the corresponding HOST (Hydrology of Soil Types; Boorman et al., 1995) classes are used to assign a FARMSCOPER soil category (Table 2).

Farming practice is simulated by FARMSCOPER using the Defra Robust Farm Type (RFT) classification scheme (Defra, 2010). Using crop areas and livestock data from the 2010 June Agricultural Survey (JAS), ‘typical’ model farms were established for each RFT for each soil and rainfall combination (Table 1) in each individual WMC. On this basis, the cropping areas, livestock counts, etc. of typical farms in each WMC were simply the averages of all available holdings belonging to any specific RFT. All possible rainfall and soil combinations within any individual WMC were then assigned to these typical farms for FARMSCOPER-based simulations. FARMSCOPER comprises a library of mitigation methods based on the Defra User Guide (Newell-Price et al., 2011), each of which is characterised in terms of its impacts on pollutant emissions and the costs or savings that implementation of the methods incur for farmers. Predicted impacts of multiple mitigation measures 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 measure 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 using a number of sources (e.g. Nix, 2009). Capital costs are typically amortised over 5 to 20 years, dependent on the expected lifetime of the corresponding investment and any associated loans. The simulations reported here used mitigation measure costs for 2013, with the predicted costs being net of any prior measure implementation associated with BAU. Costs for policy instrument administration and delivery or enforcement on the ground by agencies or officers are excluded from the simulations.

FARMSCOPER simulations using each ‘typical’ farm created for each RFT / soil / rainfall combination were aggregated across England and Wales using 2010 JAS information on the numbers of RFTs per Environment Agency Water Management Catchment (WMC). The WMCs provide 100 official reporting units although one (number 78) was discounted due to its small area (<1 km^2). Among the 99 remaining WMCs, 44% have nine and 48% have eight RTFs. Seven WMCs have fewer than eight RTFs. While the majority of WMCs are in England, eight WMCs are entirely inside Wales and five have water bodies in both countries. In total, >5000 typical model farms were created for England, >700 for Wales and nearly 400 for the border areas between England and Wales.

FARMSCOPER simulations with explicit inclusion of uncertainty, estimated pollutant emissions to water and air, resulting from existing BAU implementation of on-farm mitigation measures (E) and corresponding losses (P) resulting from a scenario specifying 95% uptake of those on-farm mitigation measures preferred by farmers surveyed in the DTCs. BAU on-farm measure implementation was estimated using a variety of data sources including the Defra Farm Practices Survey (Defra, 2009), the Defra User Guide (Newell-Price et al., 2011), questionnaire returns from Environment Scheme officers in Wales (Gooday and Anthony, 2010), questionnaire data from the Catchment Sensitive Farming (CSF) programme (Environment Agency pers. comm., 2014), the DTC baseline farm business survey and recent updates to prior implementation rates for source control measures (Zhang et al., submitted). To estimate the overall pollutant mitigation potential (R) for each individual (n = 99) WMC, the actual numbers of holdings by RFT (*H*) were combined with the simulated emissions (*E* and *P*) to estimate the percentage reduction resulting from the implementation of the new scenario using equation 1, where i is used to recognise each RFT present in each WMC and n is the corresponding number of each of the RFTs modelled by FARMSCOPER:

$$R = \sum_{i=1}^{n}\left((E_i - P_i) * H_i\right) * \frac{100}{\sum_{i=1}^{n} E_i H_i} \qquad (1)$$

The modelling assumed 95% uptake of the new mitigation scenario to assess the maximum technically feasible reductions in agricultural emissions to water and air and the associated costs or savings to farmers. This scenario of maximum potential impact was of most interest to the government policy unit funding this work. The modelled scenario with 95% implementation of the mitigation measures preferred by farmers, mapped such measures to the relevant RFTs rather than assuming a 95% implementation rate of all of the measures identified for the new policy scenario across all RFTs. This approach better reflects mitigation measure applicability to specific RFTs. The implementation rate of 95% is specified at farm scale and is based on mapping any measure to a proportion of the pollutant source areas on the farm. Projected change including uncertainty represented by the inter-quartile ranges (IQR) of predicted impacts for pollutant load reductions, was calculated relative to BAU rather than a baseline with no prior implementation of on-farm mitigation measures for diffuse pollution control. For comparison, the modelled predictions for a scenario based on 50% implementation of those mitigation measures preferred by farmers is provided in S1. The simulated impact of any mitigation scenario is not linearly related to uptake since the predicted impacts are expressed relative to BAU – i.e. the current or prior implementation of measures by farmers. The latter varies measure by measure due to a number of factors including some measures being enforced by regulation, incentives existing for some measures such as those included in agri-environment schemes and farmer uptake of different interventions varying on the basis of experience, practicality and other potential barriers including negative attitudes and restrictive costs.

Results

DTC baseline farm survey returns

In total, 87% of the farmers surveyed participate in the current entry-level (ELS) and 40% in the higher level (HLS) schemes underpinned by EU Pillar II funding for the agri-environment in England. From January 2016, these will be replaced, in England, by the new Countryside Stewardship scheme. In Wales, Glastir has been the single agri-environment scheme available to farmers, since it replaced four previous grant schemes in January 2012. There was wide variation in the extent to which the 86 on-farm measures were currently adopted in the DTC survey areas (Tables 3 and 4). In general, for the four main farm types (arable, lowland livestock, dairy, mixed farming) surveyed, and taking those measures applicable to ≥75% of the respondents, those measures with the highest current uptake were part of Cross Compliance for receipt of subsidy via the Single Payment Scheme (now the Basic Payment Scheme) under EU Pillar I funding (Tables 3 and 4).

In terms of future uptake, those on-farm measures most likely to be adopted are those which decrease the use of fertiliser (e.g. reduce fertiliser application rates) and fuel (e.g. adopt reduced cultivation systems) and thereby associated costs. The surveyed farmers were more positive towards future uptake of soil and fertiliser management options than those concerned with livestock or manure management (Tables 3 and 4). DTC farmers were more positive towards farm infrastructure improvement measures than those concerning land use change (e.g. the establishment of permanent woodlands, or arable reversion to low fertiliser input extensive grazing). Farm infrastructure measures receiving positive responses for future uptake by farmers who are currently not using them included farm track management, re-siting gateways, installing covers on slurry stores, maintaining field drainage systems, constructing bridges for livestock, fencing off rivers and streams to prevent livestock access, establishing new hedges and improving ditch management. A number of in-field measures were rated positively including the management of over-winter tramlines, moving feeders at regular intervals, using fertiliser placement technologies, adopting reduced cultivation systems and loosening compacted soil layers in grassland fields (Tables 3 and 4).

Collectively, the attitudes towards future uptake of mitigation measures provided a basis for assessing the potential environmental benefits, relative to BAU, of increased uptake (95%) of 29 on-farm interventions (Table 5) towards which the surveyed farmers were most receptive. These 29 measures were assumed to be generally relevant to all major RFTs (cereals, general cropping, dairy, less favoured area grazing livestock, lowland grazing livestock, mixed) rather than just those farm types surveyed in the DTCs, for the simulation of potential national impact. Some of the 29 measures, however, were not applicable to specific farm types. For example, increasing the capacity of slurry stores was not applicable to specialist cereal farms. The model simulations took explicit account of such applicability where appropriate. Specialist RFTs (horticulture, specialist pigs or poultry) were excluded from the scenario analysis since the DTC baseline survey did not provide responses for these bespoke farm types.

Evaluation of the BAU simulations for agricultural pollutant emissions to water and air

Evaluation of the modelled BAU pollutant emissions to water and air, with associated uncertainties represented by IQR, was based on comparison with available strategic monitoring data including 95% confidence limits, for England and Wales. The model outputs for sediment and phosphorus have been assessed previously using comparisons with field scale soil erosion rates (Collins et al., 2009a) and both catchment (Collins, et al., 2007, Stromqvist et al., 2008; Zhang et al., 2012; Comber et al., 2013) and strategic scale empirical data (Collins et al. 2009b). The predictions for sediment, phosphorus and nitrate emissions to water were also used for the quantification of agricultural contributions to total cross sector loadings by Zhang et al. (2014) who compared predicted losses with published PARCOM (Paris Commission monitoring undertaken as part of the 1992 OSPAR convention, cf. Neal and Davies, 2003 for background) monitoring data at national scale.

A number of problems and uncertainties exist for direct validation of the modelled BAU pollutant emissions at WMC scale, including the paucity of longer-term (minimum 10 years) empirical water quality data at matching temporal and spatial scales and the contribution of pollutant inputs from non-agricultural sources. There are also differences between modelled and monitored pollutant fractions and species which lead to underestimation of the full scale and impact of the emissions (Burt and Johnes, 1997; Johnes, 2007a,b; Yates and Johnes, 2013; Green et al., 2015). Since at national scale, the agricultural sector is the dominant contributor of sediment and nitrate, but not of phosphorus, loadings to freshwater (Zhang et al., 2014), the predicted BAU agricultural loadings of sediment and nitrate with corresponding uncertainty (IQR) ranges for different Water Framework Directive (WFD) river basin districts (RBDs) were compared with PARCOM monitoring (1991-2010) data with corresponding uncertainty (95% confidence limits) included (Figure 2). 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 monitored data, especially in terms of capturing the relative variations in the empirical data. Differences between the magnitudes of the modelled BAU and PARCOM data reflect a number of factors, including the modelled data representing just agricultural as opposed to all contributing sources (cf. Collins et al., 2009a,b; Zhang et al., 2014), the monitored sediment data including the organic fraction of suspended particulate matter (SPM; cf. Neal and Davies, 2003) which is not included in the modelling framework, and the different temporal coverage of the modelled and empirical datasets (2010-2013 for the modelled and 1991-2010 for the PARCOM data). Furthermore, the modelling framework only represents inland WFD cycle 2 water bodies, whereas the PARCOM monitoring data capture export to the near shore coastal environment. PARCOM loads are based on routine, but infrequent, sampling which introduces bias relative to pollutant export estimates based on higher resolution sampling (Littlewood, 1992; Johnes, 2007a; Lloyd et al, 2015) and this limitation means that it is more instructive to evaluate modelled predictions using PARCOM estimates, with associated 95% confidence limits, for longer periods (e.g. 20 years in this study) rather than for any individual years or short time periods simulated using modelling.

In the case of agricultural GHG emissions to air, the simulated BAU (represented by IQR) emissions of methane and nitrous oxide were compared with corresponding official GHG inventories from agriculture for 2013 at RBD scale (Figure 3). For consistency in the approach to evaluation, 95% confidence limits (cf. Webb and Misselbrook, 2004; Milne et al., 2014) were estimated for the national inventory data used to evaluate the modelled BAU (with IQR) GHG predictions. This comparison indicated very strong agreement for methane emissions ($r^2 = 0.97$) in terms of the relative differences between the RBDs, but revealed systematic under-prediction by the national scale modelling. Comparison of the modelled and measured BAU nitrous oxide emissions ($r^2 = 0.86$) from agriculture indicated good agreement in terms of the spatial patterns across the RBDs, but revealed a systematic over-prediction by the national scale modelling (Figure 3).

Potential costs and impacts of on-farm measures preferred by farmers for future increased adoption

Table 6 presents a summary of the annual capital, operational and total costs to the major RFTs associated with 95% uptake of those relevant interventions surveyed farmers were most inclined to implement in the future. A distinction is made between farms located either inside or outside nitrate vulnerable zones (NVZs) designated under the EU Nitrate Directive (81/676/EEC). The lowest annual capital (IQR) costs (£276 - £799 in both NVZs and non-NVZs) were predicted for the general cropping RFT, whereas the highest (£23, 957 - £38,508 and £23,964 - £38,952, respectively) were predicted for dairy farms. These contrasting estimates reflect the differing applicability of the 29 mitigation measures surveyed farmers were most inclined to implement in the future, with the most capital costly of the 29 interventions (e.g. increase the capacity of farm slurry stores to improve the timing of slurry applications, minimise the volume of dirty water produced - sent to dirty water or slurry store; Table 5) being most applicable on dairy farms. Table 6 shows that increased uptake of the relevant 29 preferred mitigation measures would generate savings in annual operational costs for all major farms types except cereals. The smallest savings in annual operational (IQR) costs were predicted for the lowland grazing livestock RFT (£1040 - £2147 in NVZs and £703 - £1754 in non-NVZs), whereas the largest were predicted for dairy farms

(£56,851 - £65,084 and £39,291 - £64,787, respectively). These results suggest that in the case of dairy farms, annual savings in operational costs associated with 95% uptake of the relevant preferred on-farm measures would off-set corresponding capital costs in most, but not all, cases (Table 6). In the case of the remaining RFTs (LFA grazing livestock, lowland grazing livestock, mixed) predicted to make savings on annual operational costs under the modelled scenario, those savings would at least offset some of the corresponding capital costs (Table 6). Annual operational (Q3) costs were predicted to increase slightly (up to £358 in NVZs and £274 in non-NVZs) for general cropping due to the increased uptake of measures requiring operational input including incorporate manure into the soil (Table **5**). For cereal farms, 95% uptake of the relevant measures from the 29 surveyed farmers were most inclined to implement in the future was predicted to increase annual (Q3) operational costs in both NVZ (£943) and non-NVZ (£818) areas.. Maximum annual total (IQR) costs to different RFTs were predicted to be generally less than £4000, with consistent savings (£14,947 - £25,773 in NVZs and £14,513 - £25,463 in non-NVZs) for dairy farms reflecting the significant reductions in annual operational costs (Table 6).

Table 7 summarises the scaled up (WMC scale) estimates of the annual costs per hectare of farmed land associated with the modelled scenario. Fixed costs due to labour and machinery were predicted to range between £0 ha^{-1} yr^{-1} and £193 ha^{-1} yr^{-1} (median £27 ha^{-1} yr^{-1}), compared with a corresponding range of -£277 ha^{-1} yr^{-1} (i.e. a net saving) to £9/ha (median -£17 ha^{-1} yr^{-1}) for variable costs (e.g. associated with fuel use). Total annual costs (Table 7 and Figure 4) were predicted to range between -£84 ha^{-1} yr^{-1} (i.e. a net saving) and £33 ha^{-1} yr^{-1}. The median annual total cost of was £3 ha^{-1} yr^{-1}. Figure 4 shows pronounced regional variation in the scaled up predicted median (plus IQR) total annual costs per hectare, reflecting the mix of RFTs in each WMC and especially the impact of the significant farm scale annual savings for dairy farms (Table 6) which predominate in the agricultural landscapes of western England and Wales. Higher farm scale total annual costs for mixed and general cropping farms (Table 6) mean that the predicted scaled up total annual costs per hectare of the modelled scenario are higher in areas dominated by these farming systems including the southeast and east of England (Figure 4). Corresponding modelled predictions of national scale costs for a policy scenario based on 50% implementation of the 29 measures preferred by surveyed farmers is presented in S1.

Figure 4 also presents estimated annual income per hectare of agricultural land. These estimates were generated by downloading RFT (major types only, not specialist pigs, poultry, or horticulture) income data collected by the Farm Business Survey for ten government regions across England and Wales. The boundaries of the government regions were intersected with those of the WMCs and regional-specific RFT incomes were assigned to individual WMCs. If a WMC is entirely inside a government region, the RFT incomes for that region were assigned to the WMC in question or, if a WMC is spread across government regions, area-weighted RFT average incomes were assigned to the WMC concerned. JAS 2010 data were used to estimate the number of RFT holdings in each WMC and these estimates were multiplied by the WMC specific RFT incomes to estimate the total incomes from agricultural land associated with major farm types in each WMC. Finally the total incomes from agricultural land assigned to major farm types were divided by the total associated land area in the corresponding WMC to estimate annual incomes from agricultural land. Comparison of the income estimates with the annual total costs (median, IQR) of the modelled scenario in Figure 4 illustrates that the latter are well within the boundaries of the former, with the predicted median costs of the policy scenario typically representing less than 5% of annual income from agricultural land (Figure 4).

Table 7 and Figures 5-6 summarise the scaled up reductions (with uncertainty ranges) in agricultural pollutant emissions to water and air, relative to BAU, associated with the modelled scenario. WMC scale reductions in agricultural nitrate emissions to water were predicted to range between 6 - 20%, compared with 6-29% for total phosphorus and 8-37% for sediment (Table 7 and Figure 5). For agricultural gaseous emissions, the corresponding reductions, relative to BAU, were predicted to range between 12 - 24% for ammonia, 4 - 16% for methane and 5 – 10% for nitrous oxide (Table **7** and Figure 6). Median emission reductions, relative to BAU, were predicted to be in the following descending order: sediment (20%) > ammonia (16%) > total phosphorus (15%) > nitrate / methane (11%) > nitrous oxide (7%). Corresponding modelled predictions of national scale impact for a policy scenario based on 50% implementation of the 29 measures preferred by surveyed farmers is presented in S1.

Discussion

Existing schemes using tax payers money aimed at reducing the environmental impacts of farming are reported to have limited benefits in terms of reducing emissions to water and air. Previous studies examining farmer response to regulation have generally reported an aversion to responsibility and high levels of resistance to prescriptive rules (Morton, 2007; Greiner et al., 2009; Barnes et al., 2009; 2013a,b). This has resulted in policy-makers becoming more interested in the extent to which voluntary approaches can be used to influence positive environmental change and deliver socially desirable outcomes (Shove, 2010; House of Lords, 2011; Barnes et al., 2013b) especially at landscape scale (Cary, 2001; Blackstock et al., 2010). The implementation rates associated with voluntary approaches are, however, typically low, thereby constraining impact.

A number of barriers exist to increased voluntary uptake of on-farm mitigation measures for pollution abatement including, amongst others, a lack of responsibility towards water and air pollution (Morton , 2007), failure or resistance to acknowledging the diffuse pollution problem (Popp and Rodriquez, 2007; Martin-Ortega and Holstead, 2013; Christen et al., 2015), the costs and practicality of measures (Bratt, 2002; McDermaid, 2005), lack of clear and consistent guidance for farmers (Widdison et al., 2004; Guillem and Barnes, 2013), overly-rigid management prescriptions (Burgess et al., 2000) and lack of robust evidence on the effectiveness of alternative or improved practices (Del Corso et al., 2015). Consequently, improved farmer participation in environmental protection programmes, even in the context of voluntary uptake, continues to require 'nudges' and especially targeted advisory support and financial compensation (Potter and Gasson, 1988; Lutz and Bastion, 2002).

The results of the work presented here provide new insight into farmer attitudes to abatement measures for diffuse pollution control and suggest, at WMC scale, that increased uptake of the 29 preferred measures could achieve substantial reductions in agricultural emissions, relative to BAU, and for negative (i.e. net savings) to low costs to farmers (-£80/ha – £32/ha). A number of factors drive farmers' uptake of diffuse pollution mitigation measures and these include education, farm size, access to information, utilisation of social networks, succession planning, experience of schemes and environmental attitudes (Toma and Mathijs, 2007; Prokopy et al., 2008; Buckley et al., 2012; Barnes et al., 2013a; Gachango et al., 2015). Several studies have explored farmer risk aversion in relation to income (Hardanker, 2006; Vollenweider et al., 2011) and the results of the DTC baseline survey reported here strongly suggest that farmers continue to be most receptive to low cost or cost-neutral on-farm measures (cf. Table 5) for diffuse pollution control.

Although the results herein demonstrate that increased uptake of those 29 measures surveyed farmers are most inclined to adopt in the future could generate substantial emission reductions, relative to BAU, criticisms remain of human development approaches founded on farmer participation. These include, amongst others, the lack of theoretical coherence (Vanclay and Lawrence, 1994) and problems associated with working with the multiple forms of knowledge generated by farmers (Morgan and Murdoch, 2000). Additionally, much water policy work has grouped farmers into a single homogenous group (Barnes et al., 2007; Oliver et al., 2009) and for simplicity, the modelling work reported here took a similar approach. The diversity and segmentation of agri-businesses means, however, that a more detailed approach is required (Blackstock et al., 2010; Guillem et al., 2015). Although the national modelling framework deployed here recognises farm business types using RFTs, it does not currently include segmentation within those basic farm types.

The EU Water Framework Directive (WFD; European Commission, 2000) is ultimately striving towards delivering good ecological status in all water bodies in Member States. Whilst the modelling results herein suggest that BAU plus increased uptake of the 29 measures shortlisted by the DTC baseline survey could deliver appreciable reductions in agricultural emissions to water, it is important to note that this does not, on its own, necessarily translate into good ecological status in terms of the relevant biological endpoints. The scale of the nutrient and sediment reductions required in many water bodies, the interactions between multiple pollutants, impact of additional stressors including hydromorphological or climate change, and the resulting outcomes for aquatic ecology, require further investigation using both experimental and modelling approaches. In some areas, potential new policy scenarios including the one reported here will not be sufficient to deliver good ecological status thereby meaning that targeted structural land cover change will be required in addition to these measures. The results of the DTC baseline farmer survey (Tables 3, 4) suggest resistance to such land cover change measures. A policy challenge (Inman, 2011) that remains is therefore how best to fund measures involving vegetation change (e.g. establish permanent woodlands) at sufficient levels to support delivery of good ecological status under the WFD.

Intelligent intervention in the agricultural sector should strive towards generating long-term positive environmental change. It therefore remains important for policy makers to recognise the underpinning cultural values influencing decision-making in the post-productivist era (Burton, 2004) where the expectation is that farmers will produce food whilst protecting wider goods and services. Capitalising on farm surveys to understand perceptions of risk and receptiveness to on-farm measures lends much needed support to voluntary 'nudges' which might help reduce the cost burden of regulation and help deliver longer-term positive outcomes. The question remains, however, of how best to deliver improved voluntary uptake of the measures in question. Previous studies have suggested that restricting farmer choice using regulations can lead to behavioural change (Uzzell et al., 2006), although a study of NVZ regulations in Scotland reported the opposite (Barnes et al., 2013b). In the context of risk of detrimental environmental outcomes from farming, a combination of compulsory compliance and voluntary approaches is likely to be best for diffuse pollution management (Moon and Cocklin, 2011; Gachango et al., 2015). Regardless of the approach taken, it will be important to continue to gather new data on farmer attitudes to diffuse pollution control options, especially in the context of the survey reported here which only reflects the attitudes of farmers in the DTCs. The technically feasible benefit of the 29 measures shortlisted by the DTC farm survey was assessed for Wales as part of the exercise reported here but ongoing work is now beginning to model bespoke potential new policy packages being considered by the Welsh Government.

Conclusion

Increased implementation of the 29 measures identified by the DTC baseline farm survey, as being favoured by farmers, has the capacity to improve the environmental performance of farming. Farmers frequently cite the lack of evidence linking specific farming practices to water or air quality outcomes and on the cost-effectiveness of on-farm interventions as barriers to improving existing uptake of interventions (Buckley, 2012). Whilst the DTC programme in England has been established to address these gaps, integrated social science and process-based modelling, as reported here, provides a means of delivering projections on the direction of change, relative to BAU, that might be achieved by alternative futures. Such evidence is useful for keeping farmers engaged with tackling their environmental impacts on water and air, especially in the context of the time lags associated with assembling empirical (e.g. by routine monitoring of pollutant emissions) evidence on the cost-benefits of on-farm interventions. Whilst such monitoring evidence is ultimately demanded by farmers, coupled attitudinal surveys and modelling scenarios provide powerful engagement tools in the meantime.

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Table 1: The relative frequency distribution of FARMSCOPER rainfall and soil combinations across England and Wales.

	Soil categories		
Annual average rainfall (AAR; 1961-90)	Free draining	Drained for arable	Drained for arable and grass
mm	%	%	%
< 600	2.5	4.5	2.4
600 - 700	8.3	8.3	9.1
700 - 900	13.1	6.8	10.1
900 - 1200	10.5	2	3.9
1200 - 1500	7.7	0.4	1.6
> 1500	7.8	0.3	0.9

Table 2: The correspondence between HOST classes and FARMSCOPER soil categories.

HOST class	Soil group	HOST class	Soil group
1	Free draining	15	Free draining
2	Free draining	16	Free draining
3	Free draining	17	Free draining
4	Free draining	18	Drained for arable
5	Free draining	19	Drained for arable
6	Free draining	20	Drained for arable
7	Free draining	21	Drained for arable
8	Free draining	22	Drained for arable
9	Drained for arable	23	Drained for both arable and grass
10	Drained for arable	24	Drained for both arable and grass
11	Free draining	25	Drained for both arable and grass
12	Free draining	26	Free draining
13	Free draining	27	Free draining
14	Drained for arable	28	Free draining

Table 3: Summary of surveyed cereal and lowland livestock farmers current uptake and attitudes towards future adoption of diffuse pollution mitigation measures.

	High current uptake (≥ 75%)	Medium to low uptake with positive future attitudes	Medium to low uptake with mixed future attitudes	Medium to low uptake with negative future attitudes
Cereals	• Cultivate and drill cross slope • Establish riparian buffer strips • Early harvesting/establishment in Autumn • Cultivate compacted tillage soils • Reduce fertiliser applications rates • Fertiliser spreader calibration • Adopt field heap storage of solid manure • Incorporate manure into the soil • Adopt reduced cultivation systems • Maintain field drainage systems • Farm track management • Establish new hedges • Leave Autumn seedbed rough	• Use fertiliser placement technologies • Re-site gateways • Manage over-winter tramlines	• Establish permanent woodlands • Use plants with improved nitrogen use efficiency	• Establish cover crops in Autumn • Loosen compacted soil layers in grassland fields • Grow biomass crops • Store solid manure heaps on concrete and collect effluent • Cultivate land for crops in Spring rather than Autumn • Use clover in place of grass • Irrigate crops to achieve maximum yield • Replace urea fertiliser with another nitrogen form (e.g. ammonium • Convert arable land to unfertilised grass • Cover solid manure stores with sheeting • Arable reversion to low fertiliser input extensive grazing • Establish and maintain artificial wetlands
Lowland livestock	• Reduce field stocking rates if soils are wet • Adopt field heap storage of solid manure	• Re-site gateways • Move feeders at regular intervals • Farm track management	• Establish new hedges • Establish permanent woodlands • Construct troughs with a firm but permeable base • Fence off rivers and streams • Compost solid manure	• Manure spreader calibration • Cover solid manure stores with sheeting • Establish and maintain artificial wetlands • Grow biomass crops • Reduce overall stocking rates • Store solid manure heaps on concrete and collect effluent • Construct bridges for livestock • Establish tree shelter belts around livestock housing and slurry storage

Table 4: Summary of surveyed dairy and mixed farmers current uptake and attitudes to future adoption of diffuse pollution mitigation measures.

	High current uptake (≥ 75%)	Medium to low uptake with positive future attitudes	Medium to low uptake with mixed future attitudes	Medium to low uptake with negative future attitudes
Dairy	• Reduce field stocking rates if soils are wet • Maintain field drainage systems • Fertiliser spreader calibration	• Use anaerobic digestion for farm manures • Reduce fertiliser applications rates • Minimise volume of dirty water and slurry produced • Construct bridges for livestock • Use fertiliser placement technologies • Install covers on slurry stores • Use slurry injection application techniques • Additional targeted straw-bedding for cattle housing • Fence off rivers and streams • Adopt reduced cultivation systems • Store solid manure heaps on concrete & collect effluent • Re-site gateways • Use clover in place of grass • Increase the capacity of slurry stores • Use nitrification inhibitors • Reduce dietary N and P intakes • Establish new hedges • Farm track management • Loosen compacted soil layers in grassland fields • Cultivate compacted tillage soils • Make use of improved genetic resources • Use plants with improved nitrogen use efficiency • Ditch management • Incorporate manure into the soil	• Cover solid manure stores with sheeting • Establish tree shelter belts around livestock housing and slurry storage • Transport manure to neighbouring farms • Establish & maintain artificial wetlands • Manure Spreader Calibration • Establish riparian buffer strips • Compost solid manure	• Allow field drainage systems to deteriorate • Grow biomass crops • Establish permanent woodlands • Out-wintering of cattle on woodchip stand-off pads • Reduce length of grazing day/grazing season • Reduce overall stocking rates • Construct troughs with a firm but permeable base
Mixed	• Cultivate land for crops in Spring rather than Autumn • Cultivate and drill across slope • Incorporate manure into the soil • Farm track management • Fertiliser spreader calibration • Reduce field stocking rates if soils are wet • Cultivate compacted tillage soils • Adopt field heap storage of solid manure	• Adopt reduced cultivation systems • Use plants with improved nitrogen use efficiency • Make use of improved genetic resources • Establish new hedges • Maintain field drainage systems • Establish cover crops in Autumn • Use fertiliser placement technologies	• Move feeders at regular intervals • Manage over-winter tramlines • Reduce fertiliser applications rates • Establish tree shelter belts around livestock housing and slurry storage • Establish permanent woodlands • Fence off rivers and streams • Manure Spreader Calibration • Establish riparian buffer strips • Loosen compacted soil layers in grassland fields • Re-site gateways • Compost solid manure • Early harvesting/establishment in Autumn	• Grow biomass crops • Arable reversion to low fertiliser input extensive grazing • Establish and maintain artificial wetlands • Reduce length of grazing day/grazing season • Convert arable land to unfertilised grass • Store solid manure heaps on concrete & collect effluent • Use clover in place of grass • Cover solid manure stores with sheeting • Reduce overall stocking rates

Table 5: FARMSCOPER measures and their associated minimum and maximum annual total costs included in the scenario to capture those options most likely to be adopted in the future by surveyed farmers in the DTCs.

Mitigation measure	Range in annual total costs (2013)*
Establish cover crops in the autumn	3612 - 4058
Adopt reduced cultivation systems	-11789 - -6308
Cultivate compacted tillage soils	2532 – 4004
Manage over-winter tramlines	123 – 147
Loosen compacted soil layers in grassland fields	1104 – 1745
Ditch management on arable land	1780 – 2795
Ditch management on grassland	620 – 986
Make use of improved genetic resources in livestock	-3390 - -2122
Use plants with improved nitrogen use efficiency	-3433 - -2863
Use a fertiliser recommendation system (Reduce fertiliser application rates in Tables 4, 5)	-2032 - -795
Use manufactured fertiliser placement technologies	-1383 - -243
Use nitrification inhibitors	815 – 976
Use clover in place of fertiliser nitrogen	-5185 - -4163
Reduce dietary N and P intakes: Dairy	1843 – 2209
Move feeders at regular intervals	928 – 1461
Additional targeted bedding for straw-bedded cattle housing	3177 - 4683
Increase the capacity of farm slurry stores to improve timing of slurry applications (Increase the capacity of slurry stores in Tables 4, 5)	997 - 4850
Install covers to slurry stores	1335 – 4850
Anaerobic digestion of livestock manures (Use anaerobic digestion for farm manures in Tables 4, 5)	-46991 - -11693

Minimise the volume of dirty water produced (sent to dirty water store) (Minimise volume of dirty water and slurry produced in Tables 4,5)	1814 – 4596
Minimise the volume of dirty water produced (sent to slurry store) (Minimise volume of dirty water and slurry produced in Tables 4,5)	1756 – 4558
Store solid manure heaps on an impermeable base and collect effluent	6053 – 8291
Use slurry injection application techniques	447 – 1844
Incorporate manure into the soil	7670 – 9177
Fence off rivers and streams from livestock	801 – 1050
Construct bridges for livestock crossing rivers/streams	732 – 1154
Re-site gateways away from high-risk areas (Re-site gateways in Tables 4, 5)	1196 – 1438
Farm track management	158 – 223
Establish new hedges	1757 - 2287

- The estimated total annual (2013) costs reflect certain assumptions about farm structure e.g. cropping areas, livestock counts, daily excreta, etc. The values are not absolute minimum and maximum values but indicative national scale ranges based on typical representative farms. Note that these estimated costs are subject to regular review and updates.

Table 6: Summary of the capital, operational and total annual costs for different major RFTs associated with 95% uptake of the 29 on-farm mitigation measures most likely to be adopted in the future by surveyed farmers. Costs are split between NVZ (nitrate vulnerable zone) and non-NVZ areas since the legislation associated with the former impacts on BAU mitigation measure uptake and thus on the predicted costs associated with future implementation at 95%.

Cost category	Robust Farm Type	NVZ			Non NVZ		
		Q1	median	Q3	Q1	median	Q3
Capital	Cereals	1068	1474	1882	1069	1474	1880
	General cropping	276	486	799	276	486	799
	Dairy	23957	33741	38508	23964	33935	38952
	LFA grazing livestock	2543	3321	3921	2323	3242	3804
	Lowland grazing livestock	3051	3819	4699	2863	3481	4286
	Mixed	5580	7746	9732	5500	7700	9780
Operational	Cereals	171	562	943	61	467	818
	General cropping	-300	-60	358	-348	-104	274
	Dairy	-65084	-56851	-39359	-64787	-56766	-39291
	LFA grazing livestock	-3078	-2378	-1411	-2872	-2017	-1092
	Lowland grazing livestock	-2147	-1508	-1040	-1754	-1122	-703
	Mixed	-6555	-4766	-3146	-6683	-4840	-3257
Total	Cereals	1433	1956	2548	1323	1843	2394
	General cropping	17	412	1121	-20	335	1034
	Dairy	-25773	-22520	-14947	-25463	-21870	-14513
	LFA grazing livestock	462	979	1558	213	1089	1781
	Lowland grazing livestock	1767	2190	2693	1476	2221	2923
	Mixed	1732	2647	3507	1631	2602	3460

= annual net saving

Table 7: Summary statistics for the WMC scale fixed, variable and total annual costs, and emission reductions relative to BAU, associated with implementing the 29 on-farm mitigation measures most likely to be adopted in the future by surveyed farmers.

Statistic	Fixed (£/ha)	Variable (£/ha)	Total (£/ha)	Nitrate (%)	Total phosphorus (%)	Sediment (%)	NH_4 (%)	CH_4 (%)	N_2O (%)
Minimum	0	-277	-84	6.0	6.2	8.0	12.0	3.8	4.7
Maximum	193	9	33	20.2	28.7	36.6	23.7	16.3	10.2
Median	27	-17	3	10.6	15.2	19.5	16.0	10.5	6.9

* The results for each individual WMC are provided in supplementary information

Figure captions

Figure 1: The Demonstration Test Catchments (DTCs).

Figure 2: Comparison of modelled agricultural sediment (upper plot) and nitrate (lower plot) emissions (median, IQR) to water, under BAU, with PARCOM (1991-2010) monitoring data (median, 95% confidence limits) collected at WFD RBD scale.

Figure 3: Comparison of modelled agricultural GHG emissions (nitrous oxide upper plot, methane lower plot), under BAU, with published GHG (2013) inventory data (with 95% confidence limits) at WFD RBD scale.

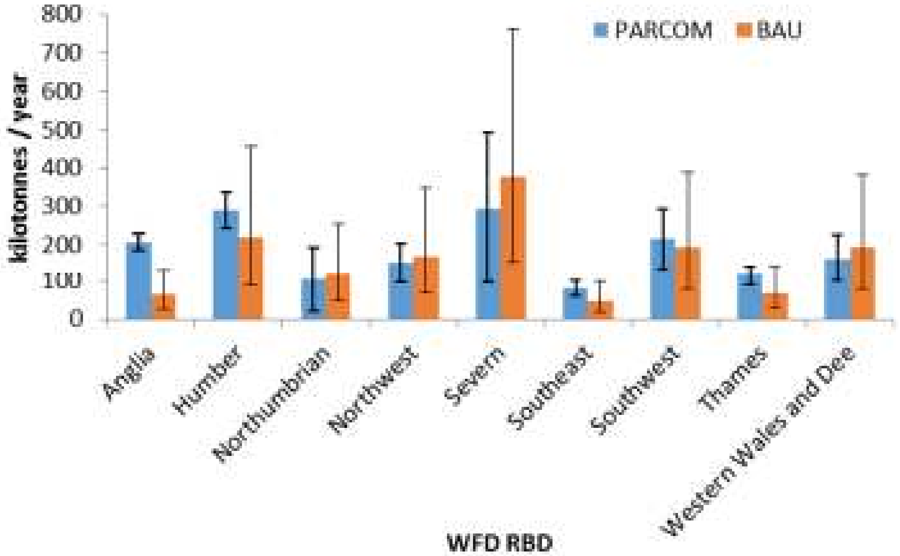
Figure 4: Predicted median and IQR total annual on-farm mitigation costs (£/ha/yr) associated with 95% implementation of the 29 measures preferred by surveyed farmers, annual income (2013-14) from agricultural land and the median on-farm costs of the new policy scenario as a percentage of annual income.

Figure 5: Predicted reductions (median and IQR) in agricultural emissions to water, relative to BAU, at WMC scale.

Figure 6: Predicted reductions (median and IQR) in agricultural emissions to air, relative to BAU, at WMC scale.

Figure 1

907



908

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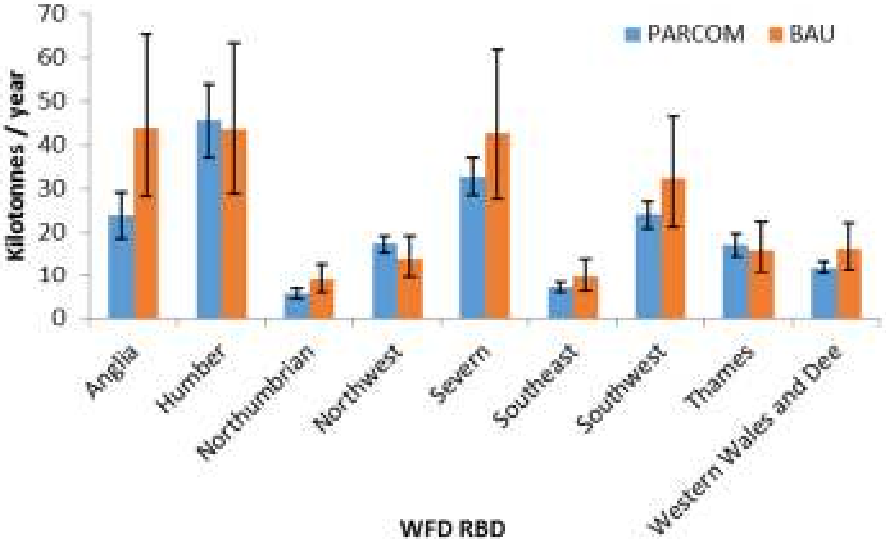


910

911 Figure 2

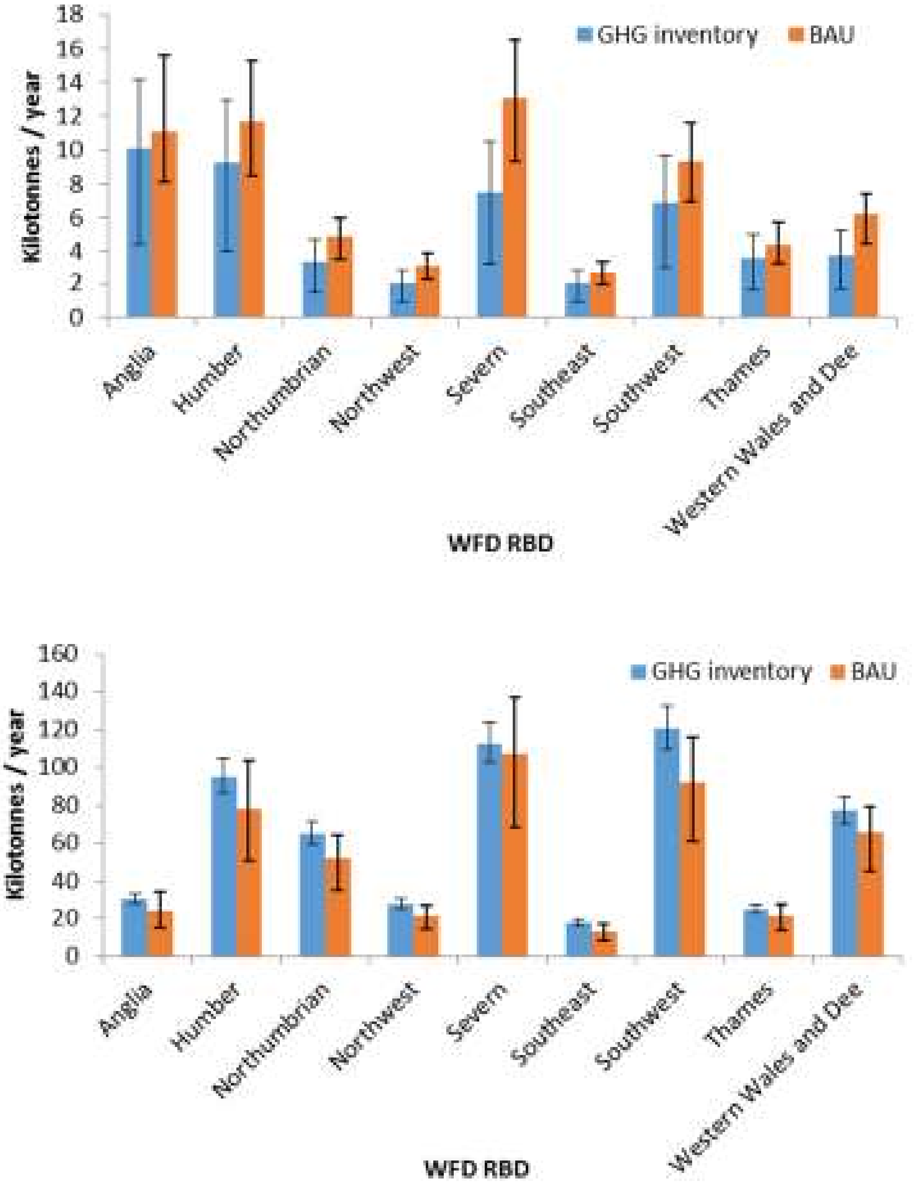

18
16
14
12
10
8
6
4
2
0
Kilotonnes / year
GHG inventory
BAU
Anglia
Humber
Northumbrian
Northwest
Severn
Southeast
Southwest
Thames
Western Wales and Dee
WFD RBD
160
140
120
100
80
60
40
20
0
Kilotonnes / year
GHG inventory
BAU
Anglia
Humber
Northumbrian
Northwest
Severn
Southeast
Southwest
Thames
Western Wales and Dee
WFD RBD

Figure 3:

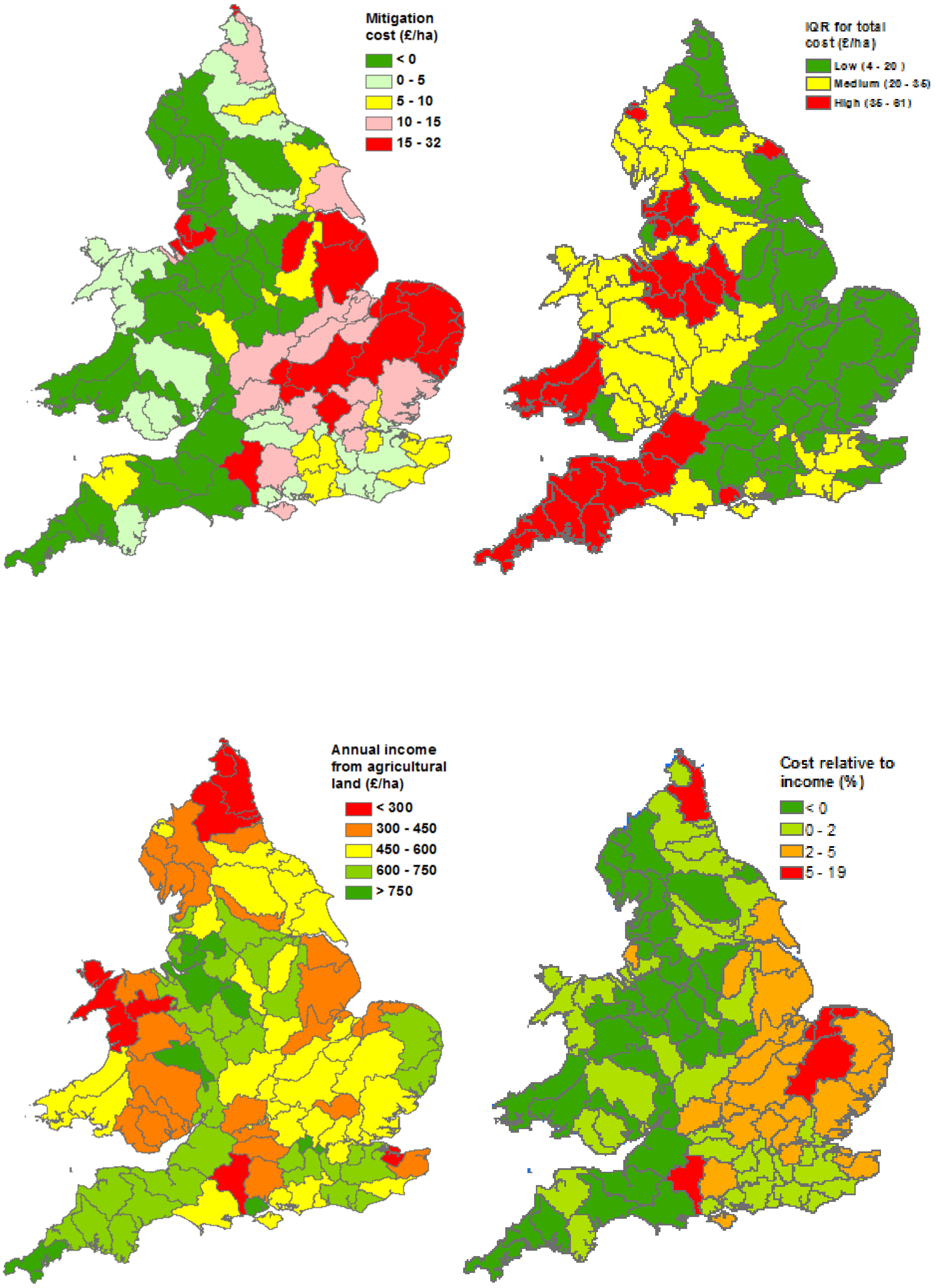
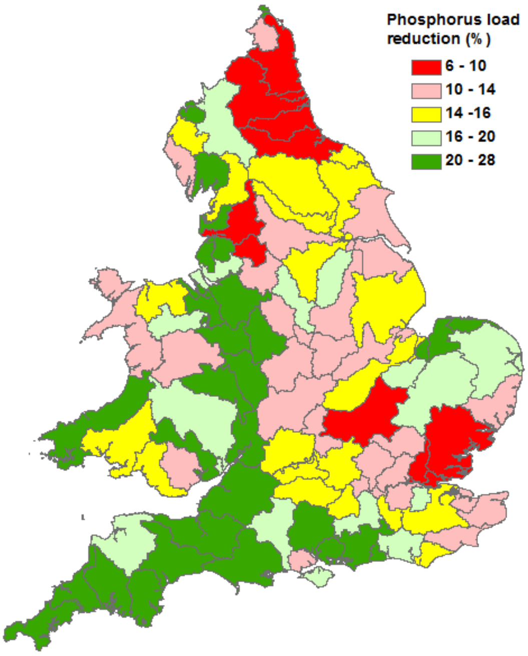
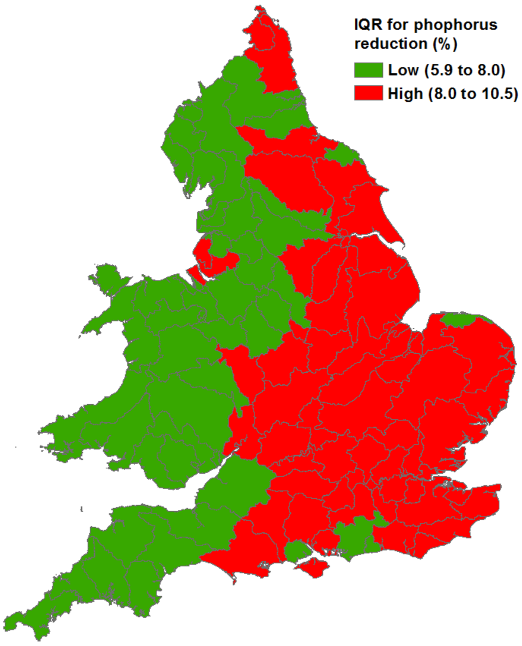
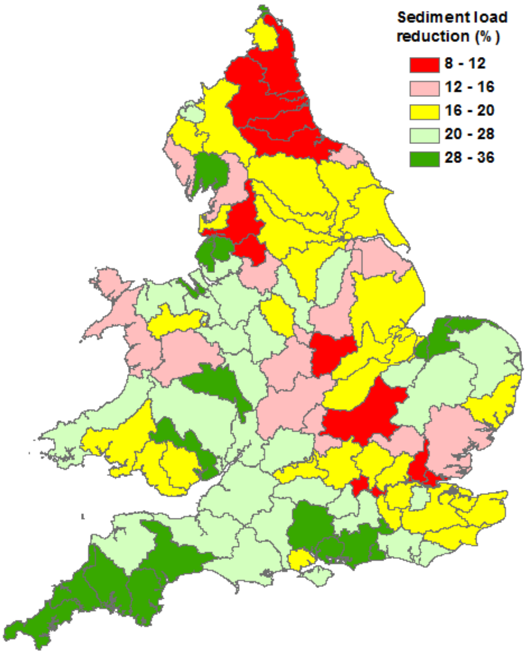
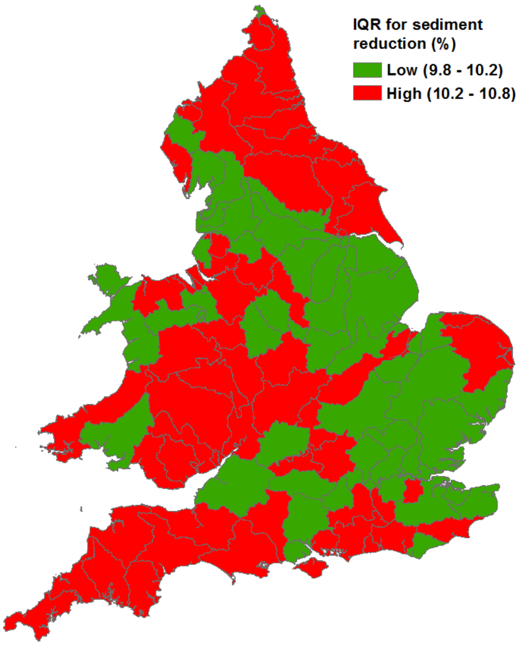

Mitigation cost (£/ha)
< 0
0 - 5
5 - 10
10 - 15
15 - 32
IQR for total cost (£/ha)
Low (4 - 20)
Medium (20 - 35)
High (35 - 61)
Annual income from agricultural land (£/ha)
< 300
300 - 450
450 - 600
600 - 750
> 750
Cost relative to income (%)
< 0
0 - 2
2 - 5
5 - 19

Figure 4


Phosphorus load reduction (%)
6 - 10
10 - 14
14 -16
16 - 20
20 - 28


IQR for phophorus reduction (%)
Low (5.9 to 8.0)
High (8.0 to 10.5)


Sediment load reduction (%)
8 - 12
12 - 16
16 - 20
20 - 28
28 - 36


IQR for sediment reduction (%)
Low (9.8 - 10.2)
High (10.2 - 10.8)

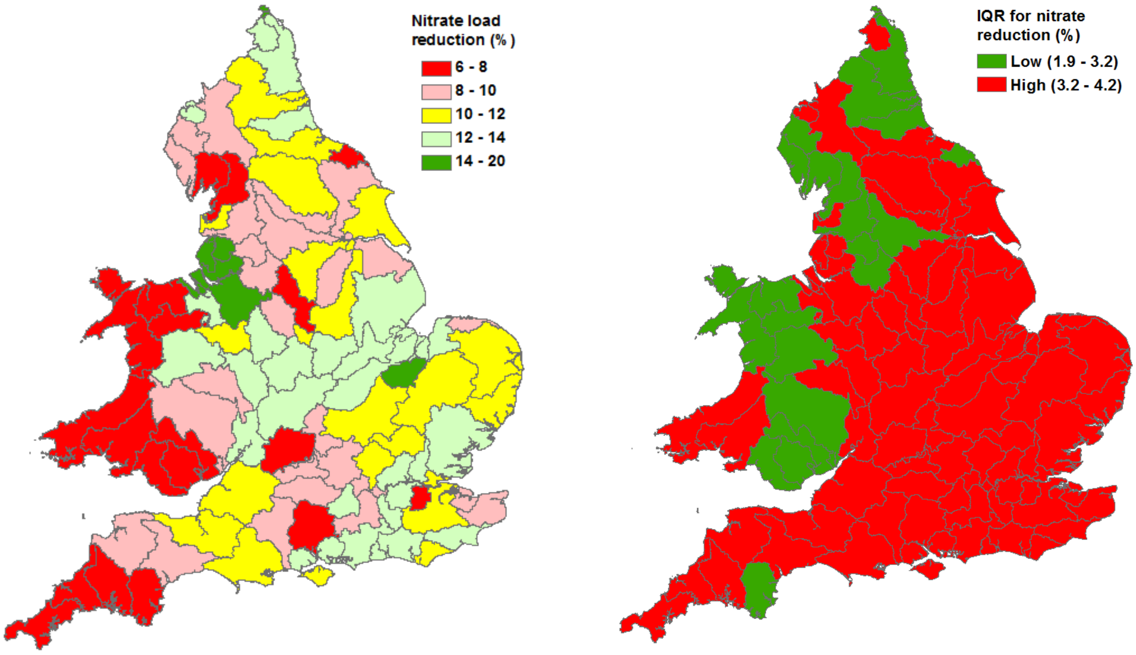
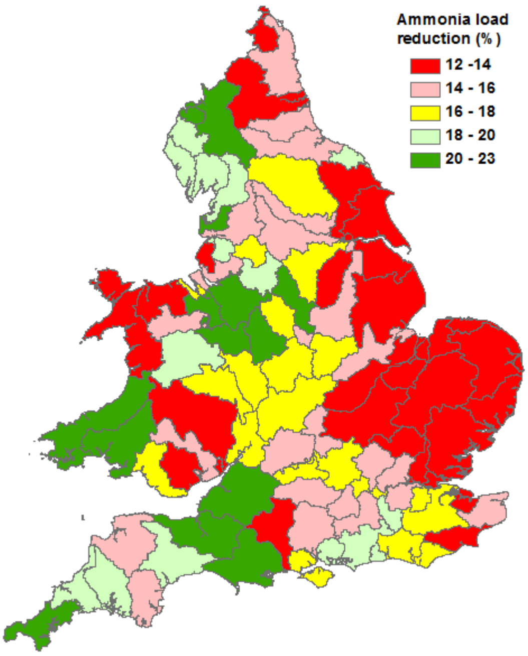
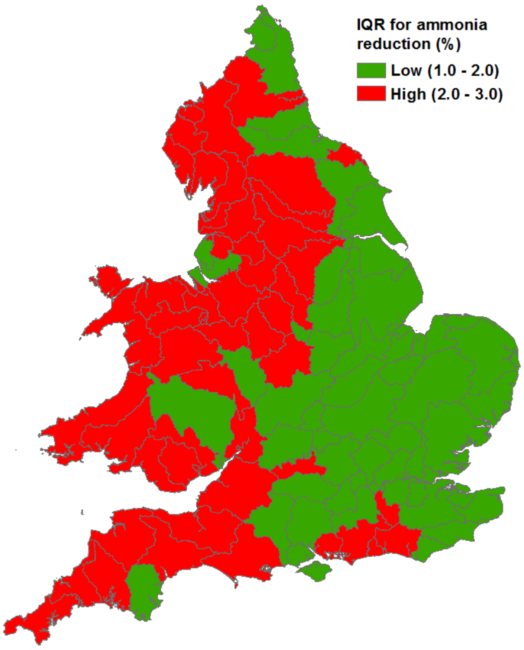
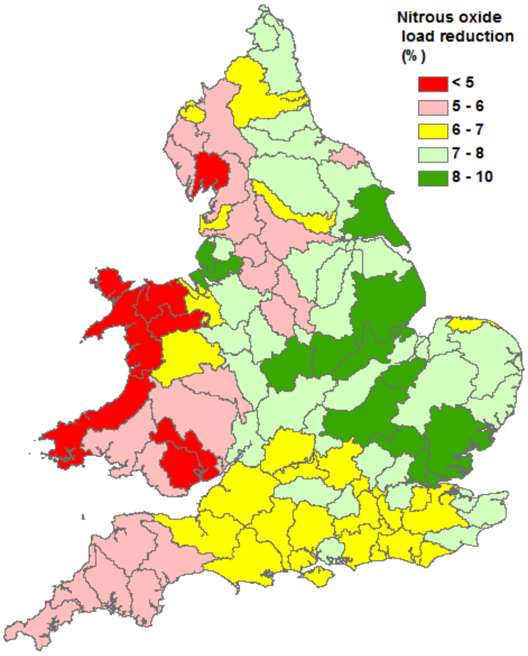
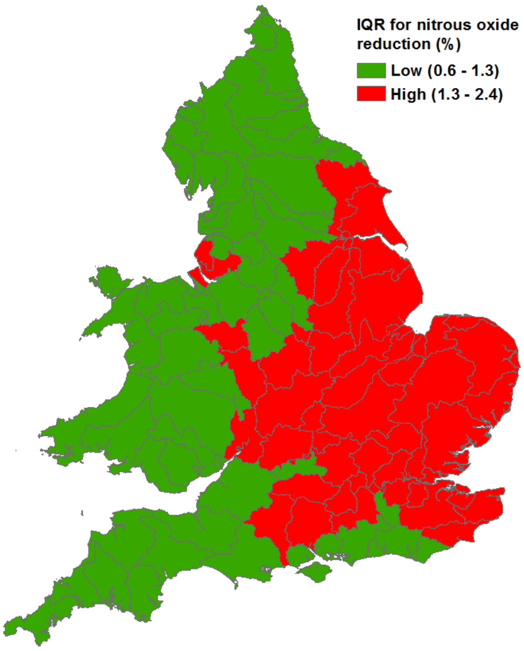

Nitrate load reduction (%)
6 - 8
8 - 10
10 - 12
12 - 14
14 - 20
IQR for nitrate reduction (%)
Low (1.9 - 3.2)
High (3.2 - 4.2)

Figure 5


Ammonia load reduction (%)
🟥 12 -14
14 - 16
16 - 18
18 - 20
🟩 20 - 23


IQR for ammonia reduction (%)
🟩 Low (1.0 - 2.0)
🟥 High (2.0 - 3.0)


Nitrous oxide load reduction (%)
🟥 < 5
5 - 6
6 - 7
7 - 8
🟩 8 - 10


IQR for nitrous oxide reduction (%)
🟩 Low (0.6 - 1.3)
🟥 High (1.3 - 2.4)

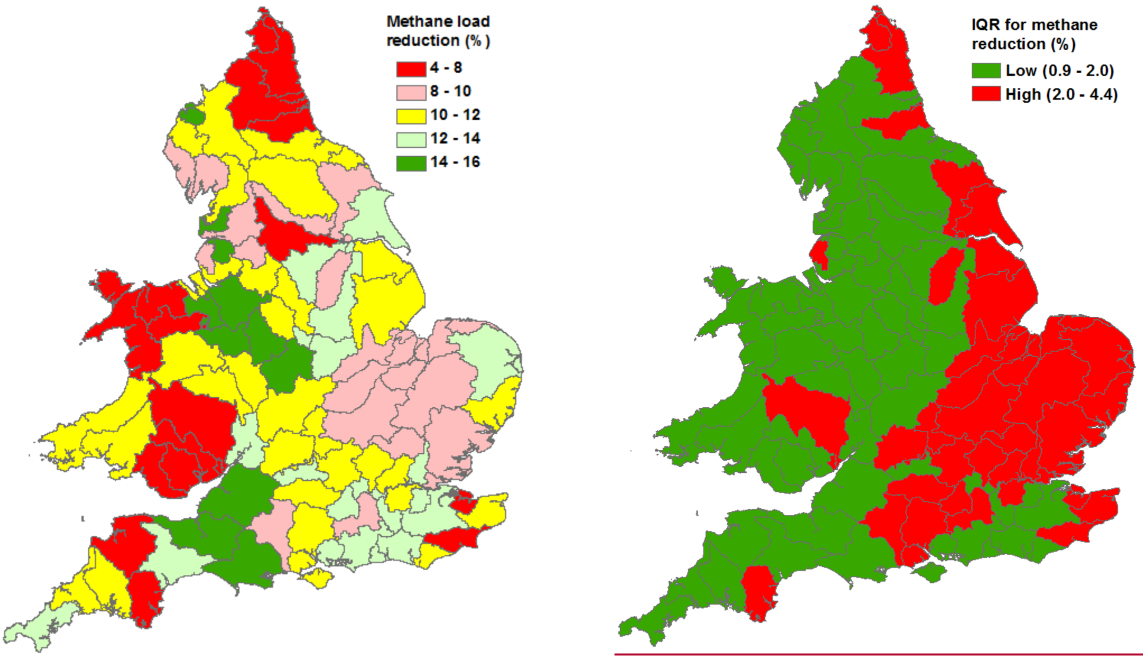

Methane load reduction (%)
4 - 8
8 - 10
10 - 12
12 - 14
14 - 16
IQR for methane reduction (%)
Low (0.9 - 2.0)
High (2.0 - 4.4)

Figure 6