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The potential benefits of on-farm mitigation scenarios for reducing multiple pollutant loadings in prioritised agri-environment areas across England

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ABSTRACT

Mitigation of diffuse water pollution from agriculture is a key national environmental policy objective in England. With the recent introduction of the new agri-environment scheme, Countryside Stewardship, there is an increased emphasis on the macro-spatial targeting of on-farm mitigation measures to reduce pollutant pressures, and a concomitant need to forecast the technically feasible impacts of on-farm measures detailed in current policy and their associated costs and benefits. This paper reports the results of a modelling application to test these limits in the context of the associated costs and benefits for the reduction of diffuse water pollution from agriculture for each Water Framework Directive (WFD) water management catchment (WMC) and nationally. Four mitigation scenarios were modelled, including pollutant source control measures only (SC), mobilisation control measures only (MC), delivery control measures only (DC) and measures for source, mobilisation and delivery control (SMDC) combined. Projected impacts on nitrate, phosphorus and sediment export to water, ammonia, methane and nitrous oxide emissions to the atmosphere, together with the associated costs to the agricultural sector were estimated for each WFD WMC and nationally. Median WMC-scale reductions (with uncertainty ranges represented by 5th–95th percentiles) in current agricultural emissions, were predicted to be highest for the SMDC scenario; nitrate (18%, 11–23%), phosphorus (28%, 22–37%), sediment (25%, 18–43%), ammonia (26%, 17–32%), methane (13%, 7–18%) and nitrous oxide (18%, 16–20%). The median benefit-to-cost ratios (with uncertainty ranges represented by 5th–95th percentiles) were predicted to be in the following order; DC (0.15, 0.09–0.65), MC (0.19, 0.09–0.95), SMDC (0.31, 0.20–1.39) and SC (0.44, 0.19–2.48). Of the four scenarios simulated, the SC and SMDC suites of measures have the greatest potential to deliver reductions in BAU emissions from agriculture, and the best benefit:cost ratio.

1. Introduction

It has long been recognised that emissions from agriculture result in the excess loadings of multiple pollutants on receiving freshwaters across England (Johnes and Burt, 1991; Heathwaite et al., 1996; Carpenter et al., 1998; McGonigle et al., 2012; Houses of Parliament, 2014a), and on increasing rates of gaseous emission to the atmosphere (Sutton et al., 1995; Skiba et al., 1997; Misselbrook et al., 2000; Houses of Parliament, 2014b). Policy approaches for controlling this pollution in England include the promotion of voluntary codes of good practice, incentivised schemes and regulation. The intention is that these approaches, in combination, alleviate environmental damage by agricultural diffuse pollution and thereby lessen the corresponding external costs to society. Incentivised schemes are best represented by agri-environment initiatives which have increasingly encouraged the uptake of combinations of on-farm measures to tackle significant pollutant pressures and to help deliver multiple policy objectives including the protection of natural resources and the maintenance of ecosystem services (Boatman et al., 2008).

Built on the evolving knowledge of the efficacy and associated costs of on-farm mitigation measures (cf., Cooke and Petch, 2007; Cherry et al., 2008; Balana et al., 2011; Schoumans et al., 2014), integrated modelling approaches have been increasingly applied as a means of combining hydrology and nutrient flux simulations with economic scenarios (Gomann et al., 2005; Mainstone et al., 2008; Moreau et al., 2012; Bouraoui and Grizzetti, 2014), to account for measure depen-

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dency and competition (Gooday et al., 2014, 2015), and the potential for pollutant swapping (Collins and McGonigle, 2008; Stevens and Quinton, 2009) or co-benefits (Johnes et al., 2007; Verspecht et al., 2012; Greene et al., 2015; Collins et al., 2016). Alongside these developments in modelling approaches for agricultural diffuse water pollution, the concept of the water pollutant transfer continuum, i.e. source-mobilisation-delivery-impact (Lemunyon and Gilbert, 1993; Haygarth et al., 2005), has been adopted widely for structuring the assessment of water pollution risk, designing mitigation strategies and targeting monitoring for the estimation of mitigation impacts (Kronvang et al., 2009; Wall et al., 2011; McGonigle et al., 2014; Murphy et al., 2015; Bloodworth et al., 2015; Zhang et al., 2017). The prohibitive costs associated with universal or blanket implementation of numerous on-farm mitigation measures, mean there is a growing trend towards the optimisation of on-farm mitigation measure selection using cost-effectiveness (Haygarth et al., 2007; Gooday et al., 2014) or farmer attitudes (Collins et al., 2016). Much previous work has compared the potential benefits of blanket measure application versus spatial targeting to address critical source areas (Johnes et al., 2007; Strauss et al., 2007; Collins and Davison, 2009; Doody et al., 2012; Shore et al., 2014). It is now widely accepted that the spatial variability of agricultural pollutant pressures has to be considered implicitly in the design of robust and cost-effective mitigation strategies (e.g. Anthony et al., 2012; Zhang et al., 2012; Greene et al., 2015; Jones et al., 2016).

In England, the Department of Environment, Food and Rural Affairs (Defra) has recently (January 2016) introduced the new Countryside Stewardship (CS) scheme which aims to ‘protect and enhance the natural environment, in particular the diversity of wildlife (biodiversity) and water quality’ (Countryside Stewardship, 2015). This new agri-environment scheme has identified priority areas which require on-farm mitigation to meet the environmental objectives associated with various national and international policy drivers, including the WFD, Bathing Water Directive, Sites of Special Scientific Interest and Natura 2000 designations, and surface or ground water safeguard zone delineations. To provide knowledge-based evidence on the technically feasible impact of new mitigation scenarios in association with the new CS scheme, several theoretical scenarios were constructed using interventions targeting the different stages of the water pollutant transfer continuum and evaluated with a national scale modelling framework. The modelling framework uses Farmscoper (FARM SCale Optimisation of Pollutant Emission Reductions) which was initially developed by ADAS UK Ltd. for the evaluation of mitigation impacts on pollutant reductions at farm scale (Zhang et al., 2012; Gooday et al., 2014). The tool has been scaled up and validated at catchment (Zhang et al., 2012) and national levels (Collins et al., 2016; Collins and Zhang, 2016) and continues to be used extensively in support of UK agri-environmental policy. This paper reports a national scale application for England, with the modelled outputs being summarised at WFD WMC scale (Environment Agency, 2015), to support the ongoing re-design of on-farm mitigation strategies since a mid-term review of CS is scheduled in 2018. Preliminary efforts were also made to explore the uncertainty ranges for the predicted efficacy of the policy scenarios tested here (e.g. Collins et al., 2016).

2. Methodology

The key procedures involved in the quantification of potential mitigation strategy cost-effectiveness at WFD WMC scale using the national scale Farmscoper modelling framework have been described in detail elsewhere (Collins et al., 2014, 2016; Collins and Zhang, 2016). In brief, the framework is underpinned by a number of national layers based on farm survey and census data, process-based modelling of agricultural pollutant losses and IPCC models (Fig. 1). More general background on the Farmscoper tool is provided in Supplementary information (SI).

2.1. Mapping agricultural pollutant pressures for the CS priority areas

The areas of high and moderate priority for CS options across England related to water quality for the period 2015–2021 were provided by the Environment Agency (Countryside Stewardship Water Quality Priority Areas v5, October 2014, Chris Burgess, pers. comm., 16 March 2015). For each designated priority area, the presence of pollutant pressures, including nutrient, sediment, pesticides, FIO and dissolved oxygen concentrations together with, river hydrology and morphology, was assessed at the site level. In the study presented here, the focus was on nitrate, phosphorus and sediment flux to waters, since agriculture is considered to be a significant contributor to these pressures (cf. Zhang et al., 2014), together with nitrous oxide, methane and ammonia emissions as key emissions from agriculture to the atmosphere. The model is currently set up for nitrate rather than nitrogen, owing to existing policy drivers for the control of nitrate pollution in waters, such as the EU Nitrates Directive (91/676/EEC). This does mean that the total impact of nitrogenous pollution from agriculture on freshwater ecosystems (see Durand et al., 2011 for a review of these other forms and impacts) is not included in this analysis.

Using ArcGIS software, the CS designated priority areas (Fig. 2) and corresponding key pollutant pressures were intersected with the WFD WMC boundaries to generate new spatial data layers of pollutant emissions. The agricultural land areas comprising CS priority zones within each WFD WMC were also determined. Although the modelling scenarios focussed on CS priority areas for water quality protection, the modelling framework simultaneously computes the costs and benefits of on-farm interventions for multiple pollutants of water and air, since many measures impact simultaneously on both receptors, enabling the potential for pollution swapping to be taken into account explicitly.

2.2. Selection of on-farm mitigation measure combinations

The concept of the diffuse pollution transfer continuum from land to water suggests that the translocation of pollutants from agricultural sources to receiving aquatic environments involves mobilisation and delivery along multiple pathways: for water these include natural flow pathways to and in conjunction with groundwater, as overland or quickflow, or via artificial (e.g. tile) drainage. In many locations, a combination of these flow paths exists. In the Farmscoper simulation tool, delivery pathways to water are characterised as leaching to groundwater, runoff (surface or shallow quickflow), preferential flow (e.g. via macropores/cracks) or direct (e.g. incidental losses). All pollutant loadings and mitigation impacts are evaluated on an annual basis. Though some monthly variations are implicitly represented, there is no explicit characterisation of event-based dynamics, i.e. storm processes for either pollutant emissions or mitigation efficacy.

On-farm mitigation measures in Farmscoper (n = 105) were reviewed for their relevance to water quality. Seven measures were considered to have insignificant potential benefits at national scale. These were: install air-scrubbers or biotrickling filters in mechanically ventilated pig housing, more frequent manure removal from laying hen housing with manure belt systems, in-house poultry manure drying, irrigate crops to achieve maximum yield, protection of in-field trees, irrigation/water supply equipment is maintained and leaks repaired and use high sugar grasses.

The remaining 98 measures were further assessed and assigned to three mutually exclusive groups targeting the stages of the water pollutant transfer continuum: source control measures (SC), mobilisation control measures (MC) and delivery control measures (DC). Another theoretical combination of measures (SMDC) included all three of the above sets as a means of assessing the maximum potential impacts of combined measures targeting the land to water continuum. The four theoretical mitigation scenarios used for modelling (SC, MC, DC and SMDC) included 59, 18, 21 and 98 on-farm measures, respectively (Table 1). The scenarios assumed measure uptake rates