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Abstract

There are high aspirations for environmental water quality targets in the UK, but requirements for significant growth in agricultural production to meet both food security objectives and provide viable livelihoods for farmers make these hard to achieve. Significant water quality challenges are related to nutrients, pesticides, pharmaceuticals, pathogens, sediments and habitat alteration. To facilitate the challenges posed, there is a need for predictive, spatially-distributed models to be developed that encompass the key aspects of agriculture and water management in order to inform future policy and organisations with an interest in land management. Additionally, there needs to be recognition from policy makers that different solutions are needed in different agri-water systems and that it often takes many years or decades for policies to have a sustained water quality impact. Long-term support for research infrastructure and the scientific skills base is required to enable measurement and data analysis necessary to inform decision making. Farmers need clearly articulated information on the issues and potential solutions on which to make informed management decisions regarding water. There are existing solutions to some problems and this knowledge needs to be effectively disseminated with appropriate incentives for implementation to have maximum impact. Greater collaboration between researchers, industry and policy makers, with the necessary framework to deliver effective joint working, is urgently needed. There is also a need for a wider societal understanding of the land-water system and the various ways in which society pays (and might pay in the future) for the real value of water.

Keywords: pollution, farming, policy, freshwater, groundwater, catchment management

Introduction

There are major challenges involved with managing land to produce food, while ensuring the availability and cleanliness of water for humans and the environment [1, 2]. Until recently, much thinking has been based on single sectors focussed on water, food or the environment. Developing a sustainable food-and-water system requires bringing expertise and thinking from the water, food and environment sectors together. Earlier papers have provided individual opinion pieces on the subject[3], studied groups of measures for reducing agricultural pollution in the UK [4, 5] and highlighted the need for better connections between research and policy formulation to mitigate UK agricultural water pollution[6]. Our paper builds upon these outputs and, importantly, provides a collaborative overview from a group of authors who are from several disciplines and from different sectors including the farming and food industry, the water industry, policy and regulatory communities, environmental science and academia. We use expert opinion to critically evaluate issues of environmental water quality associated with UK agriculture. The authors consider whether it will be possible to balance high-level aspirations for environmental water quality, with significant growth in agricultural production to meet food security objectives and the provision of viable livelihoods for farmers. We describe the nature and scale of the problem, before considering important issues around spatial variability and the potential for spatially optimised solutions. We then argue that expectations around demonstration projects need to be managed to cope with potentially long lag times for improvements in some water quality variables following intervention measures. We examine the role of regulation and voluntary measures and the need to encourage a wider societal understanding of the real value of water.

THE NATURE AND SCALE OF THE PROBLEM

Water contains dissolved and suspended organic and inorganic substances. Natural waters vary greatly in their chemical and physical characteristics related to local soils, geology, proximity to oceans and land cover. Despite this wide variability, local ecological systems can be remarkably sensitive to the introduction of chemicals in the environment, and may change rapidly as concentrations of substances change [7]. There are many different sources of water quality impairment including industrial effluent, urban runoff, sewage and septic tank releases, radioactive waste, dumping of waste into water bodies or seepage from waste sites, agriculture, and atmospheric deposition resulting from air pollution. Therefore apportioning these sources to particular water quality problems is a key challenge. Pollution is generally regarded as a significant deviation from the normal or 'natural' chemical conditions, usually as a consequence of human activity. Therefore, measuring the quality of water often involves comparing the current condition of water to its normal/natural state, a key feature of the European Union's Water Framework Directive (WFD) [8]. There are thousands of natural and human-made chemicals that can be measured in dissolved or particulate form within water, each of which could potentially be used as an indicator of water quality. However, many of these might be impractical or too expensive to measure or be ambiguous in terms of what they tell us about the overall condition of the water. Water quality standards, and what we may consider to be pollution, depend not just on what is in the water but also what the water is used for (e.g. drinking water, water for bathing). These standards have been incorporated into the WFD. The WFD is currently being reassessed by the European Commission to determine whether, almost 20 years after its inception, it is operating as effectively as it could, and there is uncertainty about whether after exiting the European Union the UK will continue to abide by the WFD or its underlying principles. However, as it stands, the WFD still plays a key role in UK and European water quality assessments and action planning. The WFD defines water quality objectives based both on ecosystem status and the end-use of the water (e.g. for drinking). There is an expectation that the water body should be in 'good ecological status' or for heavily modified water bodies 'good ecological potential' while taking account of factors such as the geology, altitude, catchment size and so on. This status may be different for each catchment, as it depends on what the local 'natural' condition might be like. However, the WFD system means that if just one assessment parameter (e.g. pH) for a water body fails to meet good status, then the water body is deemed to fail overall. The Directive requires member states to achieve objectives via River Basin Management Plans – a system of water management to coordinate regional activities. One of the main requirements of the WFD is that assessment of the probable causes of failures needs to be undertaken.

During the first two thirds of the 20th century, the main cause of negative impacts on UK fresh water quality was effluent from industrial sources and human settlements. However, over recent decades the balance of pollution sources has shifted [3]. Industrial effluent has improved due to changes in types of production in the UK and stricter environmental standards on point source discharges. At the same time, agriculture, which covers over 70% of the UK land area, has significantly intensified, leading to more productive, more efficient and larger farms. While there can be point source pollution leaking from agriculture (e.g. failure of a slurry store), much agricultural pollution is considered to occur from diffuse sources and it is therefore more difficult to monitor and attribute the pollution to particular activities or areas of land. However, the agriculture and rural land management sector has been identified as the main cause of failures in water quality due to sediment, and equal with the wastewater treatment sector as the main cause of failure due to nutrients across WFD River Basin Management Districts in the UK [9]. Currently, only 24% of surface water bodies in England and 36% of surface water bodies in Wales meet 'good ecological status' as defined by the WFD. In Scotland, 65% of water bodies are deemed good or better, but for the 35% which are failing, agriculture is deemed to be a major pressure [10]. For Northern Ireland 22% of water bodies achieve good status [11]. There are therefore major challenges for the UK, particularly for water treatment and the food and farming sector.

Agriculture affects water quality through the release of nutrients (as a result of soil management and fertiliser application) and other chemicals (e.g. pesticides) into the water environment, through biological contamination (e.g. from microbiological organisms in manure), and via soil being eroded and washed off farmland with resulting impacts downstream [8, 12, 13]. Management of agricultural land alongside river margins and banks, reducing vegetation cover, can increase exposure to incoming solar radiation and sunlight on river water, potentially increasing temperatures and the capacity to hold dissolved oxygen with direct and indirect impacts on in-stream ecosystems, including enhanced risk of nutrient enrichment [14]. Enhanced downstream peak flows and sedimentation resulting from field drainage may also impact on water quality and riverine ecosystems [15, 16].

The principal nutrients entering water bodies from farming are nitrogen and phosphorus in their various forms, which contribute to eutrophication, with associated toxic algal blooms. In the UK, around 60% of nitrate and 25% of phosphorus in water bodies are estimated to have farming origins [17]. A decrease in relative nitrogen fertiliser costs after the 1970s oil boom meant large increases in nitrogen input to the landscape but this declined from the 1980s, when nitrogen use started to be restricted on environmental grounds. However, the legacy is still apparent, particularly in groundwaters where accumulation can be slow but denitrification opportunities are limited such that increased nitrate concentrations can still be seen in many locations even decades after major reductions in nitrate [18, 19] and phosphorus [20].

Along with nutrients, the main chemical pollutants from agriculture are organic compounds, (including pesticides such as herbicides, insecticides and fungicides). The effects of these types of chemicals are complex and sometimes their degradation products can also be very harmful to aquatic life. However, highly persistent and bio-accumulative pesticides cannot be registered for sale in the EU. All pesticides must pass a rigorous risk assessment by an independent authority (the

European Food Safety Authority) to identify and exclude chemicals with these properties. For pesticides there are few WFD failures in the UK with no surface or groundwater failures in Scotland, only three in Northern Ireland (2007–2011) and 0.8 % of surface waters in England and Wales failing 'good status' because of pesticides. Just over 5% of groundwaters in England and Wales fail because of pesticides. In many cases, the substances detected in groundwaters are now banned, again demonstrating that there can be a long lag time for recovery of groundwater systems from some types of pollution. For water bodies that are used to provide drinking water the assessment standards are more stringent and up to 15 % of UK Drinking Water Protected Areas are at risk of failure due to pesticides [21]. Metaldehyde, a slug killer, is the most significant active substance, causing risk at 96 (20%) of sites in England[22]. There is still work to be undertaken on pesticide reduction in Drinking Water Protected Areas and there is a considerable ongoing cost borne by water companies to support pesticide reductions before water reaches treatment plants (~$3 billion since 1987).

There is also concern about pharmaceuticals from veterinary medicines entering watercourses and their impacts on ecological processes. These chemicals are designed to be biologically active and therefore have the potential to pose risk to aquatic and terrestrial habitats if they are released. There has been relatively little work to establish the nature or scale of the pharmaceutical problem but a recent acceleration of research in this area [23] suggests that pharmaceuticals are widespread in UK watercourses [24], although the farming-derived sources are probably far smaller than sewage-effluent sources. Avermectins such as ivermectin and doramectin and anthelmintics such as flubendazole are commonly used to kill parasites in farm animals and often used whether the animals are infected or not. As these chemicals are antiparasitic, they are toxic and can have major impacts on aquatic ecosystems. Critically, these chemicals are designed to treat several species rather than just one (unlike the case for many human medicinal pharmaceuticals) and therefore they may pose greater risk to the wider environment. Several veterinary pharmaceuticals may also be highly persistent and bio-accumulative[25]. For human medications, the medicinal emission pathway into the environment is typically via wastewater treatment plant discharge. However, for veterinary pharmaceuticals the emission into the environment may often be diffuse through urine and dung deposited across the landscape by the animals or via slurry spreading. The issues are not restricted to lowlands with upland grazing and bird sport management also potentially contributing to water quality issues within headwaters. Flubendazole is used to medicate grouse which are shot for game sports in upland catchments. However, no work has been done to establish whether this leads to high concentrations in upland streams or what impacts the chemical has on the aquatic environment.

Microbiological contaminants from livestock farming that pollute water are commonly pathogens, with indicator species of *E. coli, Cryptosporidium,* and *Campylobacter* typically used to indentify problems[26]. Sources of faecal pollution include applications of sludge and livestock waste, grazing animals defecating on land and near watercourses and discharge from septic tanks. There is relatively little monitoring of pathogens except in coastal bathing waters and areas which are major shellfish harvesting zones so the scale of the problem in freshwaters is unclear. High-resolution monitoring of microbiological contamination has not been routinely employed across catchment systems and as such there is a lack of data worldwide. The evidence base on catchment microbial dynamics is much poorer than that of sediment or nutrients[27]. However, there is a need to quantify the relative contributions from agricultural and urban sources and to ensure remediation strategies are in place where needed. Both of these are challenging because the microbial flux from agricultural systems is highly episodic and quite different between high river flow and low river flow conditions with peaks during high flow events when overland flow has been widespread across the landscape[27]. Unfortunately remediation strategies such as ponds, woodchip corrals and riparian buffer strips are likely to be least effective during high-flow events when overland flow connectivity is greatest across the landscape. For example, pond systems can effectively attenuate microbiological transport during dry weather or light rainfall, as the water retention time within the pond is at its greatest. However, following heavy rainfall, the retention time is reduced, flows from farmyards are maximised and highly turbid inputs reduce the impacts of sunlight in killing bacteria in the pond. Therefore the World Health Organisation[28] and the EU[29] both recommend use of real-time modelling to predict when water resources are likely to be most affected by microbiological contamination and therefore to avoid abstraction during these times.

Soil erosion is a natural process but farm activities can significantly accelerate the rates of erosion and transfer of soil particles and fine silt from agricultural land into waterways. Crops such as maize grown on steep slopes and bare fields left after harvest can significantly increase soil erosion risk with rill and gully development reported following storm events[30]. Ploughing or harvesting followed by wet conditions can result in significant loss of sediment from fields. Riverbank poaching by grazing animals and overstocking of fields can also lead to considerable sediment loss. On farm impacts include the loss of productive topsoil and a reduction in yields. There is therefore considerable incentive for farms to minimize erosion losses. The sediment can affect fish spawning[31] by clogging coarser bed sediments where they lay their eggs, and reducing the amount of light in the water. Some chemicals (particularly pesticides and phosphorus compounds) bind readily to soil and so may be transported through overland flow into water bodies. While apportioning sediment in water bodies to agricultural practices is challenging it is thought that 75% of sediments polluting water bodies in England and Wales are derived from farming [32].

THE TRANSFER CONTINUUM

The pathways by which water quality can be affected by agricultural management can be conceptualized by the source-mobilisation-delivery-impact transfer continuum [33]. This describes the sources of agricultural substances, the way they are made mobile, the route by which the substances are transferred to water and their impacts. Specifically, the *source* of the substance may be fertilisers and pesticides applied to the soil, livestock feed, or natural forms of nutrients held in soils and rocks. *Mobilisation* occurs when the substance leaves the field and starts its journey and involves subsidiary processes, solubilisation, detachment and incidental (i.e. direct) losses. Solubilisation involves geochemical and biological processes in the soil, such as desorption and enzyme hydrolysis, and is therefore closely coupled to soil nutrient cycling [34]. Detachment involves physical processes, for example, surface soil disturbance by heavy rain. Incidental losses involve the direct transfer of freshly applied fertiliser or manure that is washed directly into hydrological pathways without equilibrating with soil. To reach surface waters from the point of mobilisation, substances must be delivered. *Delivery* is dependent on hydrological processes and may include water flows in surface and/or subsurface pathways that vary spatially and temporally. For example, when the soil is saturated or rainfall intensity exceeds infiltration rates into the soil, water containing pollutants may flow across the land surface. However, in temperate regions such as those of the UK, most flow in watercourses is derived from throughflow; water that has percolated through the soil and drained into watercourses through shallow subsurface routes or via longer pathways through deeper groundwater. Overland flow is more likely to occur during heavy rainfall events (infiltration-excess overland flow), or after sustained periods of rainfall when the soil is saturated (saturation-excess overland flow). It is also more likely in certain areas, which may expand and contract over seasons or during rainfall events [35] such as the foot of hillslopes, along tractor wheel-ruts or animal tracks where the soil surface has been compacted, or on shallow, poorly drained soils, which are more easily saturated [36, 37]. This spatial zonation means it is possible to identify source zones for pollutants that are more likely to be mobilised by surface flows (such as pathogens), and other zones where such mobilisation is less likely. Finally, *Impact* is the resulting biophysical or indeed economic impact that may be realised downstream and could occur considerable distance and time away from the start of the continuum.

The transfer continuum can be applied to understand and help design mitigation strategies for all types of diffuse polluting substances. It is important to consider the pathway for pollutants and whether the transfer continuum can be cut off through appropriate land management to stop pollutants from reaching water bodies. The continuum concept also highlights that impacts of point or diffuse pollution from agriculture can occur quite some distance from the source and with a time lag, as long as the pollutant is mobilised and transported through the catchment to accumulate downstream. For some pollutants, particularly those associated with sediment such as heavy metals and phosphorus, then many minor issues upstream, which would have little impact if isolated, can sum to large impacts downstream due to cumulative deposition in slower moving reaches. Managing diffuse pollution may therefore most appropriately lie in prevention rather than cure, utilising best practices at the farm level to avoid the small-scale, field-level impacts that sum up to significant impacts on water quality downstream [38].

Source control considers the overall inputs and works towards better nutrient-use efficiency (e.g. the right amount of fertiliser at the right time for the crop to use), and therefore less loss of nutrients to the environment. It also involves balancing the farm's use of nutrients, considering all source inputs to the farm, including bagged fertiliser, concentrate feeds, atmospheric inputs and weathered sources from soil. *Mobilisation control* focuses on prevention of soil or nutrient loss from the field itself, and may, for example, include ploughing practices to increase the infiltration capacity and lessen soil erosion, or manure management practices to reduce opportunities for leakage. Good agricultural practices, such as avoiding application of manures and fertiliser before predicted heavy or prolonged rainfall events can reduce 'incidental losses' [39], while using slurry injection techniques or incorporating manure into the soil as soon as possible after application can reduce the risk of nutrients reaching water bodies. Efficient nutrient use will save money as well as improve water quality downstream. Indirect benefits may also accrue in the form of fewer journeys across the land thereby protecting soil structure, which in turn means a better growing medium for crops resulting in better yields. *Delivery control* involves ways of slowing and removing substances once entrained in the flowing water, for example through the use of ponds to catch sediment or buffer strips to catch nitrate and encourage denitrification of the soil water through biological activity [40].

SPATIAL VARIABILITY, OPTIMISATION AND CATCHMENT DEMONSTRATIONS

Applying the ecosystem services or landscape-scale approach to consider the wider value of different types of land-use or management change in different locations has sometimes been hampered by confusion surrounding different outcomes occurring as a result of the same management practice in different places. There are important interactions that influence the relationship between management actions, location and outcomes [41]. The transfer continuum described above suggests that spatial location is a critical factor determining the impacts of agricultural activity or intervention strategies on water quality. For example, several private water companies have been working in partnership with other stakeholders to restore degraded areas in the UK uplands. These systems are often grazed and managed for game sports but are also an important source of the UK's drinking water. Water quality and hydrological responses to the same catchment interventions in the uplands have been found to vary from place to place [42-46]. Many of the processes behind this variability are becoming better understood such as the role of topography in mediating the impacts of peatland ditch blocking on water-tables[47]. These science advances need to be explained in a form that can be utilised by the policy and practice community to inform resource allocation. This could be in the form of a set of principles or guidelines or in the form of spatial modelling tools that indicate where impacts of management change may have the greatest impact on water quality and where it is more likely that there will be little benefit,

A range of practical measures for reducing diffuse pollution from agriculture has been assessed by governments and academia [4, 48]. However, there are opportunities for innovation in the development of on-farm methods for reducing diffuse pollution that incorporate enhanced and multi-scale spatial processes. For example, it has been assumed that many of the risk-management techniques tested in lowland settings for reducing diffuse pollution can be applied in upland environments (e.g. sheep dip practices, livestock management, herbicide and fertiliser application methods, and the use of buffer zones and biobeds). However, there has been little testing of these techniques for the range of soils in UK uplands. The outcomes may be different as upland soils often tend to be organo-mineral soils which behave in different ways physically, hydrologically and chemically to mineral soils [49]. While the overall loading for pollutants from upland environments tends to be low on a national scale, this does not negate the need for further action and research given the importance of these environments for water supply and downstream ecosystem services and the potential sensitivity of naturally nutrient poor upland waters[50].

There are important opportunities for the research community to support the development of, and improvements in, spatially-distributed models of the water-land-food system. Such models can be useful tools supporting both large scale (national and regional) and small scale (farm scale) mapping of options and risks[51]. The models need to be spatially-distributed in order to i) demonstrate where in the landscape the best outcomes might be achieved from different management solutions (optimization) at different scales e.g. [52]; ii) facilitate a varied land-use system supported by a spatially-distributed policy system; and iii) guide future data collection to test model predictions about the long-term outcomes of management change. One of the key challenges is that many policy-makers desire a few broad brush models (or even one ‘unified’ model) that can be applied to cover all of the different elements of the water-landscape system. However, these sorts of models tend to be associated with high levels of uncertainty and a limited science-base and may be incredibly challenging to produce. In addition, innovation may be driven down by promoting the use of a few models rather than stimulating the development of new, more appropriate models for tackling key issues, based on more certain science. Advancing a ‘platform’ approach may be more productive whereby different models that are developed for the UK water-land-food system are done so in a way that facilitates future connections between those models. In other words, where relevant and appropriate, models should be capable of being coupled to one another. This would support the wishes of the policy community while at the same time enabling new, focused models to be developed to tackle specific issues without necessarily compromising on uncertainty levels.

As new science emerges, delivering both agricultural productivity and other ecosystem services, such as good water quality or biodiversity, could be enhanced by “smart” landscape planning making the best of local context. For example, there is a need to try to achieve an equilibrium state, balancing inputs and outputs for phosphorus within a catchment, supporting agricultural productivity while moving toward closing the phosphorus cycle. The process of balancing input and output of phosphorus flows was recently addressed as a theoretical hypothesis[53] but has been subsequently demonstrated [20]. Achieving phosphorus equilibrium will ensure efficient use, thus minimizing downstream losses and water quality impairment. Some catchments tend to accumulate phosphorus and in these cases new phosphorus imports/inputs to the catchment should be reduced and there should instead be creation of internal phosphorus sources for agriculture within the catchment. It may not be necessary to take productive land out of cultivation to support wildlife and water services. Creating grassy or flower-rich margins can trap sediment and nutrients, and provide natural pest control agents and pollinators, which are also beneficial for crop production. Technological innovation, permaculture and intercropping may also provide opportunities for sustainable food and water systems in specific locations. Different regions in the UK will vary in their capacity to contribute to production requirements and in the environmental cost of doing so. Hence farming more intensively in one region allows other regions to specialise more in the production of other ecosystem services. At the same time, within both catchments and farms we may be able to identify best locations for activities (intensive, extensive, new cultivation methods and water protection measures) by using novel spatial environmental science and modelling. In fact, there are likely to be many win-win circumstances through technological innovation. Farmers have become more aware of the need to manage farm efficiencies and their impact on the environment. In parallel, precision farming techniques have also enabled cost savings. Using fine-scale spatial mapping and soil/crop property detection from farm vehicles, combined with instruments for precision delivery of nutrients or pesticides enables direct targeting of inputs at the right place and at the right time. This targeting results in reduced costs for nutrients or other resources and a reduction in nutrient losses to water bodies.

To ensure the right configurations of spatial optimisation strategies for agricultural management requires scientifically-derived information and understanding of how the water quality and agriculture system operates at different scales. However, there is also a clear need for good governance and improved econometric analyses [54] to ensure landscape-scale and farm-scale activity supports agricultural productivity, economic viability and water and wildlife services at the same time. An example of where such wider thinking and governance is required at a national scale (i.e. beyond the needs of single catchment), comes from the spatially distributed problem of UK manure supply and demand. As farming systems have become less mixed, manure-related pollution issues are pressured around those livestock systems that generate the manure, predominantly in the west of the UK. However, there is an unmet nutrient (and organic substrate) need from the arable sector in the east of the UK, generating the potential for manure to be recycled. This is also the case for human sewage sludge cake – yet water utilities are struggling to find places for disposal in the west due to saturation with nitrate and phosphorus, but have no economically feasible means of sending it eastwards where nutrients and organic matter are required. So finding a solution to the prohibitive economic cost of transporting nutrients in the form of manure or slurry from an area of excess to an area of need, would be beneficial.

We are still some way short of providing reliable data and models from farm to catchment scale that show how water quality will respond to different interventions in different locations, and therefore we are also limited in our ability to adequately assess the economic and non-monetary benefits of interventions [55]. Nevertheless, whole catchment agricultural schemes are strongly advocated in the UK to deal with water quality issues. These schemes are most commonly facilitated by agencies of the devolved UK governments or by water companies (Table 1). Catchment partnership approaches are now central to UK approaches to managing water quality. Many of them showcase cross-community working and encourage others to take up some of the farm and catchment-wide practices. However, these demonstrations often lack wider societal engagement, although the recent work of water companies in promoting their catchment work to customers has been very welcome. Overall, beyond the catchment demonstrations at a local scale, there is no coherent national framework for translation of science into policy and action on the ground with regard to agriculture, the environment and water in the UK, although there are farming advice schemes in certain sensitive catchments such as the Catchment Sensitive Farming programme lead by Natural England (Table 1). More work is required to join up catchment demonstration projects nationwide, link cutting-edge university research farms together and build their capacity, and co-ordinate research efforts nationally to develop a national strategy for novel science-policy-practice to support water and food initiatives [6].

The key lessons to date that can be drawn from the UK catchment demonstration programmes combined, including the official UK Demonstration Test Catchments (Table 1), are: i) the need for science-based evidence in a format suitable for and accessible to different audiences that makes better use of a range of media and presentation techniques); ii) a clear baseline of good practice that is enforced by regulation that provides a level playing field for all farmers and ensures catchment coverage; iii) a partnership approach ensures all organisations involved in water quality and farming have one clear and consistent message; iv) it is key to have one to one visits by well-trained agency staff who understand agriculture and farmers with a focus on advice on compliance and support for applications to appropriate funding schemes; v) patience is required for many of the anticipated outcomes to emerge.

Table 1. Examples of UK catchment-based programmes for reducing agriculture’s impact on water quality

Scheme	Key features
Scotland’s diffuse pollution plan	14 priority catchments identified that contain some of Scotland’s most important waters for conservation, drinking water, bathing and fishing. High priority given to those areas affecting human health (i.e. drinking water protected areas and catchments draining to bathing waters). Coordinated approach across Scotland to reduce diffuse pollution from rural sources. One to one visits to all farmers in priority catchments to advise them on their regulatory responsibilities and to encourage them to apply for funding for measures to improve water quality and the wider environment. Measures include regulations (General Binding Rules) based on widely accepted standards of good practice, which provide a level playing field for all farmers and a clear baseline above which funding is used via the Rural Development programme. Measures are implemented via a two-tier approach of national awareness-raising and targeted action in priority catchments.
Catchment Sensitive Farming	Developed in England to address agricultural diffuse pollution issues through a voluntary, incentivised approach. Free, practical advice and training to farmers and land managers on how to reduce diffuse water pollution from agriculture, across 80 Priority Catchments (targeted to meet WFD requirements and improve freshwater Sites of Special Scientific Interest. Officers are responsible for individual catchments, coordinated at River Basin District level and they encourage changes in behaviours and practices by engaging with farmers through workshops, seminars, farm demonstrations, self-help groups and undertaking one to one farm visits; co-ordinate Steering Group activity; undertake communications and publicity; signpost agri-environment schemes and other incentives; and assist farmers with Capital Grant applications.
Catchment Based Approach	Partnerships at catchment, sub-catchment or watercourse level to focus on tackling issues in a collaborative way. Draws on existing community partnerships (e.g. Campaign for the Farmed Environment (CFE), Local Nature Partnerships, Nature Improvement Areas, Local Enterprise Zones) and initiatives and allows new ones to develop at a local level.
Natural Resource Management approach	Natural Resources Wales are developing priority catchments, where the drive is from government (top down). The Welsh Government is also supporting a number of self-assembled groups who have put themselves forward presenting proposals for landscape scale co-operative projects to test bottom-up holistic approaches.
Demonstration Test Catchments	Set up in England in 2010 bringing together land and catchment managers, researchers and policy makers around focused, long-term demonstration platforms, showcasing problems and potential solutions. Four contrasting catchments: Eden - livestock and upland farming; Wensum - large intensive arable farming systems; Hampshire Avon - mixed lowland farming; Tamar - lowland dairy farming. Aim to deliver evidence in a wide range of agricultural environments; support for an ecosystem services approach to catchment management; close links to stakeholder communities to check/test; focused technical advice; mitigation plan advice; policy approaches; supporting data and information; local understanding (local/general advice).
Sustainable Catchment Management Programme	This scheme has run since 2005 and is operated by United Utilities, who own large upland water supply catchments, working with farm tenants and conservation partners with significant investment in moorland restoration, woodland management, farm infrastructure improvements and watercourse protection. The work is now focussing on activities around key drinking water safeguard zones working closely with stakeholders.
Upstream Thinking	South West Water’s catchment management scheme applying landscape-scale solutions to water quality issues since 2008. Working with the expertise of partners, the knowledge of farmers the aim is to improve raw water quality at source across 750 farms and 1300 ha of moorland. Farm advisers visit farms and produce whole-farm plans including a water management plan with capital investment proposals. These can include improvements to slurry storage, fencing, alternative water sources for livestock, and better pesticide management. Work to block drainage ditches to restore peatland is also funded.
Yorkshire Uplands	Yorkshire Water, a large private utility have invested in peatland restoration, worked in partnership with water@leeds to undertake comprehensive monitoring of peatland restoration benefits in upland catchments since 2007 that demonstrates: i) the reduction of costly water colour and dissolved organic carbon in stream waters for some types of peatland restoration; ii) improved saturation of the peat which both reduces the loss of carbon from the land and encourages more carbon to be drawn out of the atmosphere to form the peat; iii) less sediment entering streams; iv) improvements in upland stream ecology benefiting biodiversity and v) the value of long-term monitoring, assessment and research.

RESPONSE TIMES AND FUTURE PROJECTIONS

There are often long lag times between best management practices being implemented and improvements in water quality[56]. Work in the UK uplands has shown that initial responses to management interventions can be quite different to those that unfold several years after the interventions once the system starts to change [57, 58]. Some responses to restoration activity in the uplands can be quick such as a reduction of erosion and sediment entering streams in some catchments. However, for other benefits to be realised it may take years or even decades. Some parts of the water quality system can be very slow to recover from earlier pollutant inputs, particularly in the groundwater zone (e.g. nitrate pollution or pesticides in some groundwaters). In many high-profile cases internationally[56], intended reductions in catchment phosphorus fluxes have not occurred as quickly as expected or desired by catchment managers. Increasingly, this lagged response has been recognized to result from the large build-up of phosphorus in the topsoil, and the complex release patterns in catchments and their rivers [53]. This means that the changes that take place in the topsoil take considerable time to manifest in the upstream waters and eventually at the basin scale, something that is often popularly referred to as the legacy effect [20].

The time-lags described above are a challenge for both lowland and upland water quality demonstration projects because some of the key variables that demonstration projects are targeting may not change even many years after significant intervention. For many stewardship measures there are limited data to describe their impact at the catchment scale [4]. Thus modelling predictions or ‘lead indicators’ (e.g. change in land use) are being utilised to show the direction of travel until changes in water quality are detected by monitoring [19]. Because some interventions may take considerable time to have a water quality impact, incentives for promoting pro-water interventions ought not to be based on evidence of immediate outcomes. There needs to be a recognition that the processes and consequent solutions need to operate over both the short and long term. Mitigation measures need to address current practices and the legacy of past pollution or disturbance. There is also a clear role in supporting long-term monitoring. Long-term data collection is a vital tool for evidencing the impacts of environmental change and directly informing policy[59]. Many UK water quality monitoring networks have been short term and often risk-based. However, there is a consistent network of long-term monitoring sites across the UK although there is a sparse upland network which has only been operating since 1988[60]. It is critical that these monitoring networks are maintained, even when public finances are squeezed, to support understanding of environmental change and to provide a vital starting point for determining cause-effect and short versus long-term responses of the water system to environmental change. There are also substantial opportunities to mine the existing datasets using multivariate techniques. Even though some long-term records may have data gaps, multivariate studies that pull together data spatially from a range of different sites may be useful. For example, Vaughan and Omerod[61] , using a multivariate data pooling and analysis approach, recently found increases of freshwater invertebrates across England and Wales related to improvements in water quality. Resourcing programmes of work that utilise existing monitoring networks and water quality datasets should be encouraged, yet this type of science is rarely seen as significantly 'step-change' by many research funders.

Lag times for water quality response to management change also need to be placed within a climate change context as we try to project what the future may hold [62]. Climate change could affect all forms of agricultural production via changes in temperature (e.g. livestock may require more water, soils may dry out more requiring more irrigation), rainfall (amount, intensity and pattern through the year) [63, 64], river flow and groundwater recharge, and plant physiology (e.g. responses to increasing atmospheric CO_2 concentrations altering plant water-use efficiency [65], or increasing heat/drought stress). These factors may all impact on water quality by affecting farm management and the volumes of water flow, pathways for water movement, and the associated transfer of pollutants from agricultural land to water bodies. Projected increases in rainfall intensity and warmer, wetter winters for the UK [66] will affect hydrological pathways and therefore could impact on diffuse pollution [67]. Warmer, drier summers, may lead to changes in soil structure such as crusting or cracking, which means that when high intensity rainfall follows, it will be more likely to follow faster routes to the river channel. In many UK catchments, a few storm events each year currently transport a very high proportion of both phosphate and sediment load to the river [68, 69]. Changes in river flow regime will impact water quality and if there is less volume available for dilution then point sources of agricultural pollution will yield higher concentrations in water bodies e.g.[70]. Warmer temperatures in water bodies will accelerate biological and chemical processing thereby increasing the risk of algal blooms. Thus, on the ground solutions that may have been effective in the past for achieving water quality standards in agricultural areas may no longer be so effective under climate change or may require greater investment to deliver the same outcomes. Modelling work has, to date, revealed rather complex outcomes from climate change on water quality, which are dependent on catchment characteristics, and location within the catchment [71]. However, internationally (reflected in the relatively short sections on water quality in Intergovernmental Panel for Climate Change reports) there has been very little research to quantify the effects of climate change on water quality. Understanding climate change impacts on water quality within the agricultural sector is a major research gap that needs to be addressed.

POLICY – REGULATION AND VOLUNTARY PRACTICE

One of the major policy tools for agricultural incentivisation has been the European Common Agricultural Policy (CAP), which, since the 1960s, has stimulated food production and trade. The CAP is a farm support scheme, which now accounts for approximately 40% of the EU's budget and is linked with the management of 50% of its land area. The majority of farmers in the UK have historically opted in to receive support through CAP. This has boosted production and use of fertilisers, but some recent CAP schemes encourage a range of environmentally sensitive farming methods.

In December 2013 the European Parliament completed the latest reforms of CAP. Direct payments to farmers (known as Pillar 1) now require farmers to comply with at least one of three compulsory 'greening measures', as well as meeting statutory management requirements, plant protection product rules, and maintaining their land in good agricultural and environmental condition. The latter includes requirements to establish buffer strips and no-spread zones near watercourses, as well as soil management to limit erosion, maintain organic matter and soil cover. Beyond compulsory measures, additional voluntary measures are available within the Rural Development Regulation (known as 'Pillar 2'). Member States must spend at least 30% of their EU rural development allocation on environmental measures. This includes investments in agri-environment schemes, organic farming, WFD payments and forestry. However, there is evidence that some of these stewardship measures have been less effective than they could have been through a lack of robust implementation and targeting [5].

Nevertheless, there are some good examples of innovative approaches to balancing regulation and voluntary measures to best effect such as those of First Milk which collaborates with its 300 local dairy farmers to reduce nutrients leaving their farms with bespoke nutrient management plans in a catchment in Wales[72]. The forecast reductions in nitrate, phosphate and sediment losses into a sensitive river system in Wales are used to offset the entire outflow of the cheese factory's new effluent plant which processes 250 million litres of milk per year. Another example of balancing regulation and voluntary action is in UK pesticide management. The implementation of the EU Directive for the Sustainable Use of Pesticides [73] requires a National Action Plan [74] to be developed by each Member State. The plan provides a framework for reducing the risks and impacts of pesticide use on human health and the environment, promoting the use of integrated pest management and of alternative approaches or techniques such as non-chemical alternatives to pesticides. Specific measures in the UK plan include mandatory training for operators and distributors, inspection of application equipment, regular calibration checks, and aerial applications to be limited to permitted uses only. The UK plan also advocates non-regulatory approaches as much as possible via the Voluntary Initiative (www.voluntaryinitiative.org.uk). This initiative has been deemed a success in both reducing pesticide impacts and educating farmers in conservation measures, showing that farmers can make a profit while supporting conservation e.g. [75].

There are also opportunities for the UK to develop some policy flexibility that supports adaptive management. This would involve the research community helping to quantify the effectiveness of conservation or pollution mitigation measures in collaboration with the agricultural community enabling them to adapt those practices that are or are not working. To be effective such approaches would need to be undertaken far beyond the more restricted set of demonstration projects that are exemplified by Table 1.

VALUE OF WATER

Managing catchments to meet a range of objectives presents challenges to science in understanding what might work but also social and economic challenges given that different actors may be unaware, economically unable or disinterested in changing behaviour to reduce issues elsewhere. In the UK, more needs to be done to raise awareness to society as a whole of the connectedness of land and water systems, the true value of water and the potential role of different parts of the community in protecting land and water services [76]. There is a linked chain of actors who all have an individual part to play in influencing food production (Figure 1) and therefore land management, and in turn the impact of farming on water and the environment in general. Each actor in the chain has a responsibility in environmental protection but because they are removed from the immediate impact of the farmer’s activities they often do not recognise their role, or responsibility. This includes consumers who generally want more for less cost at the supermarket but do not necessarily recognise that there may be a trade-off between water costs and food costs, such that more intensive production may impact upon water quality, leading to greater costs for water treatment. There is a broad public and political expectation of cheap food in the UK which is reflected in the competition between supermarkets who consequently put pressure on their suppliers, be they added-value suppliers or farm businesses directly, to cut costs. This leads to farming necessarily focussing on maximising volumes of production at low costs. As a result, enhancing environmental conditions on-farm may be seen as a luxury. However, there is also a growing movement towards high quality, more expensive food in the UK and some supermarkets also apply pressure on farmers to apply greening measures in support of the particular ‘sustainability’ brand of that supermarket chain. Greater public debate could be encouraged about whether approaches are adopted to ensure the cost of food fully reflects the related costs to water and the environment or alternative ways of paying for ecosystem services are provided.

To improve public engagement with water quality, further steps could be taken to connect land managers with other catchment users of raw water, most notably water companies. The costs that water companies incur removing farm inputs from the water are not widely raised or discussed for various reasons, primarily to prevent public concerns about water quality. Where this connection has been made the willingness to work in partnership has been strong from both parties. These connections are growing with water companies given the flexibility by the water supply regulator in the UK to engage with landowners upstream of their facilities [77]. The water industry has demonstrated that this simultaneous localised and catchment-wide approach, has great significance for water security. Strong evidence of ‘willingness to pay’ by water customers for better river flow, quality and enhanced biodiversity has enabled South West Water, for example, to propose further work to improve water systems from farmed land. These approaches present real opportunities to not only develop an understanding of the relationships between securing clean water and growing food, but to also change the way those in a catchment interact. However, there are two difficulties for the UK water industry: i) the water industry typically operates on a five-year timescale, because this is the timescale of price reviews (and hence financial planning) demanded by the regulator, which makes it difficult to commit to long-term catchment management schemes and ii) water companies tend to be risk averse as there are strict standards in place for the sector. There are large perceived risks associated with a catchment management approach for water companies because they do not typically own all of the land within their catchments and they are therefore relying on others to deliver water quality improvements. However, water companies are required by the UK water industry regulator to produced 25-year water resource plans. A similar 25-year plan for catchment water quality may also be highly beneficial to ensure long-term thinking and actions beyond the normal five year financial planning timescales.

Conclusion

We suggest that the following opportunities should be pursued in order to achieve high environmental water quality in the UK while ensuring food security and viable livelihoods for farmers at the national scale:

i) New and improved, predictive, spatially-distributed models are required that encompass key aspects of agriculture and water management and which inform future policy and commercial interests. There should be work to develop and improve models for water quality *and* food production, which predict the long-term costs of food production against the real cost of the environmental trade-offs (e.g. benefits of land sharing versus land sparing). These models will support spatially-distributed management and policy decisions from farm scale to national scale.

ii) There needs to be recognition from policy makers and industry that different solutions will be needed in different agri-water systems. There is a strong requirement to embrace the challenges of scale and heterogeneity in agriculture and water quality. These present both an on-going research challenge yet also an opportunity for providing new and diverse solutions and mitigation.

iii) Decisions involving agriculture and water need to be made based on a long-term perspective; with appreciation of the time it takes for policies to have sustained impact. There is a need to recognise that the relationship between agriculture and water operates on a long-term timescale of decades. Any policies or voluntary initiatives may need this timeframe to elicit a response. Researchers and policy makers, industry and regulators should be united in recognition of the need for novel and innovative perspectives on long-term decision making and funding.

iv) Long-term support for research infrastructure is required to measure and analyse data necessary to inform decision making. There is a need to maintain appropriate depth and resilience in supporting water and agricultural research and innovation infrastructure, including long-term monitoring networks, analytical tools and the skills base to investigate patterns in data collected from across the UK. This infrastructure and skills base is required to allow research and major advances into the highly complex and only partially understood agricultural production-water system. Such advances will also inform the development of models outlined in (i).

v) Farmers need better information on which to make informed management decisions regarding water management with appropriate incentives for implementation to have maximum impact. Currently there is no framework for translation of science into policy and action on the ground with regard to agriculture, the environment and water in the UK. Farmers are the focus of numerous policies, environmental and economic factors that affect their businesses but advice is often perceived to be contradictory. There is a need for better coordination of the range of policy information and scientific research data available - targeted at a farming audience - and framed in a way that takes account of trade-offs between different environmental, economic and agronomic objectives. Mechanisms are required to encourage wider uptake of the growing number of solutions that support food production, financial outcomes for businesses while reducing or minimising negative impacts on water quality.

vi) Greater collaboration is required between researchers, industry and policy makers with the necessary framework to deliver effective joint working. Only by working in a more collaborative way will the challenges around food security in a changing climate be addressed. There is a need for building a more coordinated community around agriculture and water quality that closely aligns researchers, industry and policy makers to: coordinate activities across sectors and disciplines; develop more strategic, long-term approaches to joint working; pool resources, data and knowledge; work across a multidisciplinary environment and different industries; and improve communication and uptake of findings.

vii) There should be concerted action to educate society on the true value of water. There is a need for greater understanding of the agri-food chain and the potential environmental and water costs of low food prices. Consumers need to understand their role in the chain while the water industry needs to be encouraged to work beyond five-year financial timeframes so that they can support more catchment-based approaches.

We are optimistic that high aspirations for environmental water quality in the UK can be achieved in general (but not everywhere) while ensuring UK food security and viable livelihoods for farmers at the national scale. There could be locations where a political decision is made to trade-off water quality for agricultural production and vice versa, although these sorts of decisions need to be built upon improved science of spatial processes and optimisation modelling, in order to keep such areas to a minimum. There are significant challenges in finding and targeting cost-effective solutions. However, there are opportunities through developing our process understanding, supporting data collection, supporting innovation and farm and catchment demonstration, clever implementation of policy, communication and governance mechanisms and by developing new spatial models of interlinked agricultural production and water quality that can support policy planning at different scales, the UK should be able to deliver solutions for agricultural growth without putting environmental water quality at further risk. That will also mean tackling other sources of water pollution in parallel as part of an integrated landscape-scale approach.

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