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ENVIRONMENTAL EVIDENCE

SYSTEMATIC MAPS

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How effective are on-farm mitigation measures for delivering an improved water environment? A systematic map

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Abstract

Background: Agricultural activities are estimated to contribute 70% of nitrates, 28% of phosphates and 76% of sediments measured in UK rivers. Catchments dominated by agriculture also have elevated levels of pesticides and bacterial pathogens. European member states have a policy commitment to tackle this pollution through the water framework directive. Here we report on the results of a systematic map to investigate and describe the nature and coverage of research pertaining to the effectiveness of 6 on-farm mitigation measures, slurry storage, cover/catch crops, woodland creation; controlled trafficking, subsoiling and vegetated buffer strips for delivering an improved water environment in terms of a reduction in nitrogen (N), phosphorus (P), sediment, pesticides and faecal indicator organisms (FIOs) or pathogens from faecal material.

Methods: Research evidence for the effectiveness of the 6 on-farm mitigation measures for delivering an improved water environment (as detailed above) was collated using English language search terms for temperate farming systems in Europe, Canada, New Zealand and northern states of the United States of America. Searches for literature were made from online publication databases, search engines, specialist websites and bibliographies of topic specific reviews. Recognised experts, authors and practitioners were also contacted to identify unpublished literature. Articles were screened for relevance at title, abstract and full text using predefined inclusion criteria set out in an a priori published protocol. All relevant articles were mapped in a searchable database using pre-defined coding and critically appraised for relevance and reliability. Articles reporting the same study were removed. All full text studies without confounding factors were identified and coded for in a separate searchable database.

Results: A total of 718 articles were included in the database. Buffer strips were the most commonly studied intervention followed by cover crops and slurry storage. Little evidence was found for woodland creation and sub-soiling. No studies were found for controlled trafficking on grassland. Nitrogen was most frequently measured, followed by P, sediment, pesticides and FIOs or pathogens from faecal material.

Conclusions: The majority of the evidence collated in this map investigated the effectiveness of buffer strips and cover crops for improving water quality. This evidence was predominantly focussed on reducing N pollution. An evidence gap exists for the impact of cover/catch crops in reducing leaching of pesticides, FIOs and pathogens, and for organic forms of N and P. There was limited research investigating the effectiveness of buffer strips for reducing leaching of organic forms of N or P, or for pesticides that are currently authorised for use/commonly used in UK agriculture. Further, long term studies across different seasons with controls, pre and post water quality measurements and multiple sampling points from both field and rivers would improve the evidence base. Evidence gaps exist for woodland creation, subsoiling and controlled trafficking on grassland.

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Keywords: Buffer strip, Cover crop, Catch crop, Slurry, Woodland creation, Subsoiling, Controlled trafficking, Water quality, Nitrogen, Phosphorus, Pesticide, Sediment, Faecal indicator organism, Pathogen

Background

European agriculture has intensified over the last 50 years, leading to increased usage of fertilisers and agrochemicals [1]. Soil compaction and reductions in organic matter content resulting from intensive practice have increased the risk of soil erosion and water run-off. Nutrient applications in excess of plant needs, coupled with increased run-off from agricultural land, has contributed to a decline in water quality [2]. In the UK, for example, agricultural activities are estimated to be the source of 28% of phosphates, 70% of nitrates and 76% of sediments in rivers [3, 4], and catchments dominated by agricultural land use have elevated levels of bacterial pathogen counts [5].

A decline in water quality has increased water cleaning costs, reduced reservoir capacities and can have negative impacts on wildlife and flood defences [6]. Climate change scenarios suggest that the UK will experience wetter winters, and warmer, drier summers. Increased extreme weather events may increase the likelihood of heavy rains washing soil and pollutants into river systems, and drier summers will concentrate levels of pollutants in rivers [7].

European member states have a policy commitment to tackle water pollution through the water framework directive (WFD) and its integral components namely, the Nitrates, Ground Water and Bathing Water Directives [7]. During the last 10 years the UK Department for Environment Food and Rural Affairs (Defra) and the Environment Agency (England and Wales) have funded catchment projects to improve water quality at a cost of around 70 million pounds [8]. This included studies to assess the effectiveness of mitigation measures [9].

This study reports on the results of a systematic map to investigate the effectiveness of 6 on-farm mitigation measures for delivering an improved water environment in terms of a reduction in levels of any form of N or P, sediments, pesticides and faecal indicator organisms (FIOs) or pathogens from faecal material:

1. Slurry storage to reduce pathogens in slurry, and pollution incidents from spills and leaks [10].
2. Fast-growing cover/catch crops, planted over winter to minimise soil erosion and reduce runoff and ensure that nutrients stay in the root zone [11–13].
3. Woodland creation to improve soil structure and water infiltration and reduce runoff [14, 15].
4. Controlled trafficking (confinement of farm machinery to certain areas of a field) of grasslands to reduce soil erosion and compaction, and water runoff [16].
5. Subsoiling (breaking up of compacted soil layers) to reduce compaction, and water runoff [17].
6. Vegetated buffer strips to trap sediments, reduce pollutants and immobilise soluble nutrients through plant uptake or microbial degradation [18, 19].

Objective of the systematic map

The primary question of this systematic map was:

How effective are cover or catch crops, woodland creation, controlled trafficking on grassland, subsoiling, buffer strips and slurry storage as on-farm mitigation measures for delivering an improved water environment?

This question has the following components:

Population Controlled waters as defined in section 104 of the Water Resorces Act and include territorial, coastal, inland and ground waters [20].

Interventions Slurry storage, cover/catch crops, woodland creation, controlled trafficking, subsoiling, buffer strips.

Comparator Absence of intervention or variation of intervention.

Outcome Impact on water quality in terms of change in any form of N or P, sediment, pesticides and FIOs or pathogens from faecal material.

Methods

This question was commissioned by the UK Department of Environment, Food and Rural Affairs (Defra) to describe the nature and coverage of research pertaining to the effectiveness of 6 on-farm mitigation measures to deliver an improved water environment. Study design was discussed with the stakeholder group comprising; Defra, the UK Natural Environment Research Council (NERC), the Environment Agency (UK) and the Forestry Commission (UK). The methods used in the development of the systematic map followed the Collaboration for Environmental Evidence Systematic Review Guidelines [21] and from an existing systematic map report [22]. A scoping search was performed to validate the methodology, and is detailed in a review protocol [23], which was used to inform the final methodology. Only the systematic map element from the published a priori protocol is presented here.

Searches

A comprehensive search of multiple information sources attempted to capture an un-biased sample of literature to encompass both published and grey literature. Searches were conducted in 2012.

Search terms

The search terms for the database and web searches are listed in Table 1.

Wildcards (*) were used where accepted by databases/search engines to pick up multiple word endings. Keywords were also made more restrictive by the addition of qualifiers. Keyword and qualifier combinations varied for each intervention. Where not already used as a qualifier, each search string was appended with 'AND water' if more than 900 search results were retrieved.

The exact search strings used differed between databases. Details of the terms used in each of the search facilities employed are provided in Additional file 1.

Databases

The following online databases were searched to identify relevant literature for the primary question: ISI Web of Knowledge involving the following products: ISI Web of Science; ISI Proceedings, Science Direct, Wiley Online Library, Ingenta Connect, Index to Theses Online, CAB Abstracts, Agricola, Copac and Directory of Open Access Journals.

Search engines

Further internet searches were performed using the search engines: http://www.Scirus and http://scholar.google.com. The first 50 hits were examined for appropriate data.

Specialist sources

Websites of relevant specialist organisations were identified by the review team and stakeholders, and were also searched for relevant material. Websites were searched manually, by navigating through the site 'Publications' sections, if available, and also by using any provided automated search with a number of key search terms. The first 50 hits from organisational websites were examined for appropriate data.

A full list of organisational websites searched is given in Table 2. Topic specific bibliographies of meta-analyses and reviews were searched for relevant articles missed by the previous searches [15, 19, 24–26], as well as reference lists e.g. the list of buffer strip studies maintained by Corell [27] (http://www.unl.edu/nac/riparianbibliography.htm).

Recognised experts, practitioners and authors were contacted for further recommendations and the provision of relevant unpublished material or missing data.

Endnote database

The results of each search were imported into separate EndNote X2TM library files and then combined into a

Table 1 Keywords and qualifiers used in the literature search

Mitigation	Keyword	AND Qualifier
Slurry storage	Slurr* stor* Animal waste lagoon* Animal waste stor* Slurr* lagoon* Slurr* tank* Dairy lagoon*	Water qualit* Water pollut* Control of pollut* Nitrat* OR Nitrogen Phosph* Nutrient loss*
Woodland	Afforest* (Wooded OR woodland*) AND (agricult* OR arable OR grass*) (Shelterbelt* OR windbreak* OR hedge*) Spray drift and tree*	Bacter* Fecal OR faecal Pesticid* Sediment*
Buffer	Riparian AND (buffer* OR zone* OR filter* Or strip* Filter strip* Vegetat* AND(buffer* OR barrier*)	River* OR Stream* OR Catchment* Leak* OR Seap* OR Spill* Ground* water*
Controlled trafficking	Wheel* AND compact* AND grass* Traffic* AND compact* AND grass* Soil compact* AND grass* Controlled traffic* AND grass*	Run off OR runoff Directive* OR Europe* Infiltrat* Leach*
Subsoiling loosening compacted soil	"Subsoiling" Loosen* Compact* Deep ripping	Water AND (Erosion OR Erod*) Eutrophication Water
Cover crop/catch crop	"Cover crop" OR "Cover crops" OR "Covercrop" OR "Covercrops" "Catch crop" OR "Catch crops" OR "Catchcrop" OR "Catchcrops"	

Exact keyword and qualifier combinations varied in order to optimise searching efficiency and were informed by a scoping search.

Table 2 List of specialist organisations websites searched

Defra Online Databases
Environment Agency
NERC Open Research Archive
Forestry Commission/Forestry Research
Centre for Ecology and Hydrology
Natural England
Countryside Council for Wales
Scottish Natural Heritage
Scottish Environment Agency
Northern Ireland Environment Agency
European Environment Agency
European Commission Joint Research Centre
Finnish Environment Agency
Ministry of Agriculture and Forestry (Finland)
Swedish Environment Agency
Danish Environment Agency
Ministry of Food, Agriculture and Fisheries (Denmark)
Government Norway Portal
Flemish Environment Agency
Ministry of Food, Agriculture and Agri-food Canada
Environment Canada
US Department of Agriculture
US Environment Protection Agency
Agency of the Environment and Energy (France)
Federal Environment Agency (Germany)
Federal Ministry of Food, Agriculture and Consumer Protection (Germany)
Netherlands Environmental Assessment Agency
Department for the Environment, Transport, Energy and Communication (Switzerland)
Environmental Protection Authority (New Zealand)
Ministry of Agriculture and Fisheries (New Zealand)
Food and Agriculture Organisation of the United Nations
Ecologic Institute and EU Cost (European Cooperation in Science and Technology)

single library. Google Scholar and organisational web search results were imported into spread sheets.

Study inclusion

Study screening

An iterative process was used to filter out non-relevant articles in a two stage process, firstly to screen out completely irrelevant subjects (e.g. subjects such as mining and medicine) and secondly to filter out more closely related but irrelevant articles (e.g. air pollution and plant pathology). All articles were manually examined by at least title before being excluded.

Articles retained were screened for relevance applying inclusion criteria in three stages; title only, abstract, and then full text (where available). Where there was insufficient information to exclude an article, at any stage, it was carried forward to the next stage. A record was made of the number of articles included and excluded at each stage of the screening processes.

Inclusion criteria were applied by one reviewer, except where there was uncertainty, when two reviewers examined the text and a consensus agreement was made. To assess and limit the effects of between-reviewer differences in determining relevance, two reviewers (LD and NR) applied the inclusion criteria to a random sample of 50 articles at the title or abstract level. A kappa statistic was calculated using the online calculator http://www.graphpad.com/quickcalcs/kappa1.cfm. Duplicates and irrelevant articles were removed from Google search results using the procedure outlined for the main search results. Search results from organisational web sites were checked by title for relevance. Those that passed the inclusion criteria were then examined at abstract/full text by following the web links. The remaining Google scholar and web site search results were combined with the main search results before the final stage of screening at full text, and any duplicates removed.

Inclusion criteria

All retrieved articles were assessed for relevance using the following inclusion criteria, which were developed in collaboration with funders, stakeholders and subject experts.

- Population: Articles that investigated the effectiveness of one of the on-farm mitigation measures to improve water quality of controlled waters [20] irrespective of scale. Stakeholders agreed that the review should focus on temperate countries with similar farming systems to the United Kingdom (UK). Those countries were: UK, Ireland, France, Belgium, Switzerland, Germany, Holland, Luxembourg, Liechtenstein, Denmark, Sweden, Norway, Finland, Austria, Slovakia, Poland, Hungary, Czech Republic, Romania, Lithuania, Latvia, Estonia, Belarus, Ukraine, Canada and New Zealand and northern states of the United States of America (USA) as defined as all states that were entirely above the bottom of Oklahoma (so excluding states such as Georgia, Mississippi, Texas and California).
- Intervention: Articles measuring the effectiveness of the following on-farm interventions in improving water quality were included:

    - Buffer strips: Studies measuring the impact on water quality of buffer strips composed of trees/grass/shrubs, including shelterbelts and hedges.

Studies of wetlands (unless wetland adjacent to buffer strip) or floodplains were excluded.
- Slurry storage: Studies measuring seepage of slurry from slurry storage, studies measuring changes in counts of FIOs or pathogens over time with slurry storage (excludes changes in N or P or air pollution studies), and studies measuring the impact on water quality of the timing and amount of slurry applications. Studies of solid manure storage were excluded.
- Cover/catch crops: Studies of cover/catch crops or crops grown for winter cover and effects on water quality. Winter wheat or volunteer weeds were categorised as cover/catch crops if they provided ground cover in the same manner as a traditional cover/catch crop.
- Woodland creation: Studies measuring changes in water quality after afforestation of former agricultural land. Studies growing trees for biomass and testing their potential in cleaning waste water were also included, as were studies measuring the impact of crops intercropped with trees on water quality. Studies that compared water quality between different land uses (forest, urban, arable, grassland) or measured changes in soil nutrient cycling after afforestation were excluded. Woodland buffer strip studies were also excluded as they were included in the intervention 'buffer strips'
- Subsoiling: Subsoiling studies that measured water quality. Studies that measured water quality after the break up/loosening of compacted soil layers.
- Controlled trafficking on grassland: Studies that measured the effect on water quality of controlled traffic on grasslands.

- Types of comparator: Absence of intervention or variation of intervention. Studies with a no mitigation treatment (e.g. cropped or bare ground plots) were categorised as controlled studies, whereas studies using measurements over time and space were considered to have within treatment comparative measures and are referred to in this text as 'with comparator'.
- Types of outcome: Water quality (irrespective of experimental scale) was measured by changes in the level of any form of N, P, sediment, pesticide, FIO (e.g. total coliforms, faecal coliforms, *Escherichia coli*, faecal streptococci, enterococci or clostridia species) or pathogen from faecal material (e.g. protozoan pathogens such as *Cryptosporidium* species and bacterial pathogens such as *Salmonella* and *Campylobacter* species and *Yersinia enterocolitica*). FIOs are used to provide an indication of pathogen presence in water. Therefore in this review studies reporting FIOs have been grouped together with studies investigating pathogens from faecal material. Studies were included that estimated water quality from soil samples, or that measured slurry leakage or changes in counts of FIOs or pathogens over time in slurry. Studies that measured inferred impacts (e.g. soil infiltration rates, crop yields, plant biomass, denitrification rates, mineralisation of soil N and pesticide drift) were excluded.
- Types of study: Only studies that reported primary research investigating the effect of an intervention on water quality were considered for inclusion in the review, which therefore excluded review articles and modelling studies.

Database and repository searches were conducted in the English language. No date restrictions were applied.

Systematic map

Coding

Key wording was used to describe, categorise and code articles in the systematic map database. Keywords were generated from the primary question, the scoping study, topics reported in the included research, existing systematic maps and expert knowledge. Articles were either coded on full text, abstract or title depending upon the availability of text. The definitions of the categories and codes used in the systematic map are detailed in Additional file 2. For some categories multiple codes were applied, (for example, articles that reported results from more than one country or had multiple water quality measurements). Coding was moderated between reviewers (25% of articles were checked by both reviewers and any ambiguities discussed).

Systematic map database

A searchable database of coded articles for the primary question was created in Microsoft Access to describe the water quality research for the topic specific mitigation measures. Two database tables were created (Additional file 3):

1. Water Quality Map Title Abstract Full Text: All articles coded, at title, abstract or full text. All evidence was coded with country of study, mitigation and water quality measurement, if the information was missing, 'not clear' was recorded. In addition full text articles were coded for study design, and those articles without confounding factors (i.e. where the effects of interventions or contribution of causal factors can be separated and there are no other factors influencing the outcome of the study) were coded for

outcome. Data in this table were used to calculate the hierarchy of evidence by filtering for articles coded at full text and with articles reporting the same study removed.

2. Water Quality Map Full Text: All studies without confounding factors coded at full text. Articles reporting same study were also removed.

Critical appraisal

Hierarchy of evidence

An overall indication of the relevance and reliability of evidence available for each intervention was calculated based on scoring of standard categories for included articles for each intervention. Every article coded in the systematic map at full text (including articles with confounding factors) was given a value according to a hierarchy of evidence adapted from systematic review guidelines used in public health [28] and conservation [29], and using a system adapted from a method outlined by Pullin and Knight [30]. Articles were given values for their design, based on categories applied in the systematic map database (Table 3). The values for each category were combined for each article, and these were then collated (mean and standard deviation) for each intervention.

Results

Overall review descriptive statistics

Number and type of studies

A schematic showing the numbers of articles that were included and excluded at each stage of the systematic mapping process is shown in Fig. 1.

Table 3 Scoring system used to assess hierarchy of evidence

Category	Score	Hierarchy of evidence
Randomized	1	Yes—randomized (includes partial)
	0	Not randomized
Control	3	Controlled BACI
	2	Control
	1	Comparator
	0	None
Study length	1	Study length greater than or equal to a year
	0	Study length less than a year
Replicates	2	Replicate temporal (includes time series) and spatial
	1	Replicate temporal or spatial
	0	No replicates
Study type	3	Manipulative study
	2	Correlative study
	1	Monitoring study
	0	Sampling study

Adapted from: Pullin and Knight [30].

A total of 718 articles were judged to have met the inclusion criteria based on either title, abstract or full text review and were included in the systematic map (Database 1 of Additional file 3). A Kappa score of 0.588 indicated moderate agreement [31] for inclusion between reviewers and this was considered acceptable for this type of systematic map based on CEE guidelines [21]. The majority of articles were journal papers (n = 494), followed by conference papers/posters (n = 118), reports (n = 44) and theses (n = 27). The remaining articles (n = 35) were either books or the article type was unclear. Four meta-analyses were also found in the search process [17, 22, 23, 32]. The earliest article retrieved, dated from 1950 after that date no articles were published until 1971. A substantial increase in articles was seen from the early 1990s onwards.

Of the 718 articles, 467 met our additional criteria that articles should be at full text and not report on a study already included in another article.(Where a study was reported more than once, the article with the most comprehensive information was carried forward to the next stage). These articles were used to calculate the scientific rigour of the evidence for each intervention. The 467 articles were further assessed to remove any with confounding factors resulting in 410 articles. The number of articles removed with confounding factors was similar for each intervention.

Trends available in the evidence for all mitigations

Preliminary trends were investigated using all the 718 articles. These trends remained consistent after articles were removed to meet the additional criteria. Studies often investigated multiple mitigations or outcomes or were performed in more than one country. This results in discrepancies in the total number of articles reported.

Intervention type

Buffer strips (including woodland buffers) were the most commonly reported intervention (n = 364), followed by cover/catch crop (n = 245). Fewer articles reported slurry storage (n = 93), woodland creation (n = 24) and subsoiling (n = 10). No articles were found for controlled trafficking on grasslands.

Geographical location

The majority of articles originated from the northern states of the USA (n = 256) and these predominantly investigated buffer strips. The remainder of the articles originated from Europe, and most were from the UK (n = 80) where cover/catch crops were reported marginally more frequently than buffer strips.

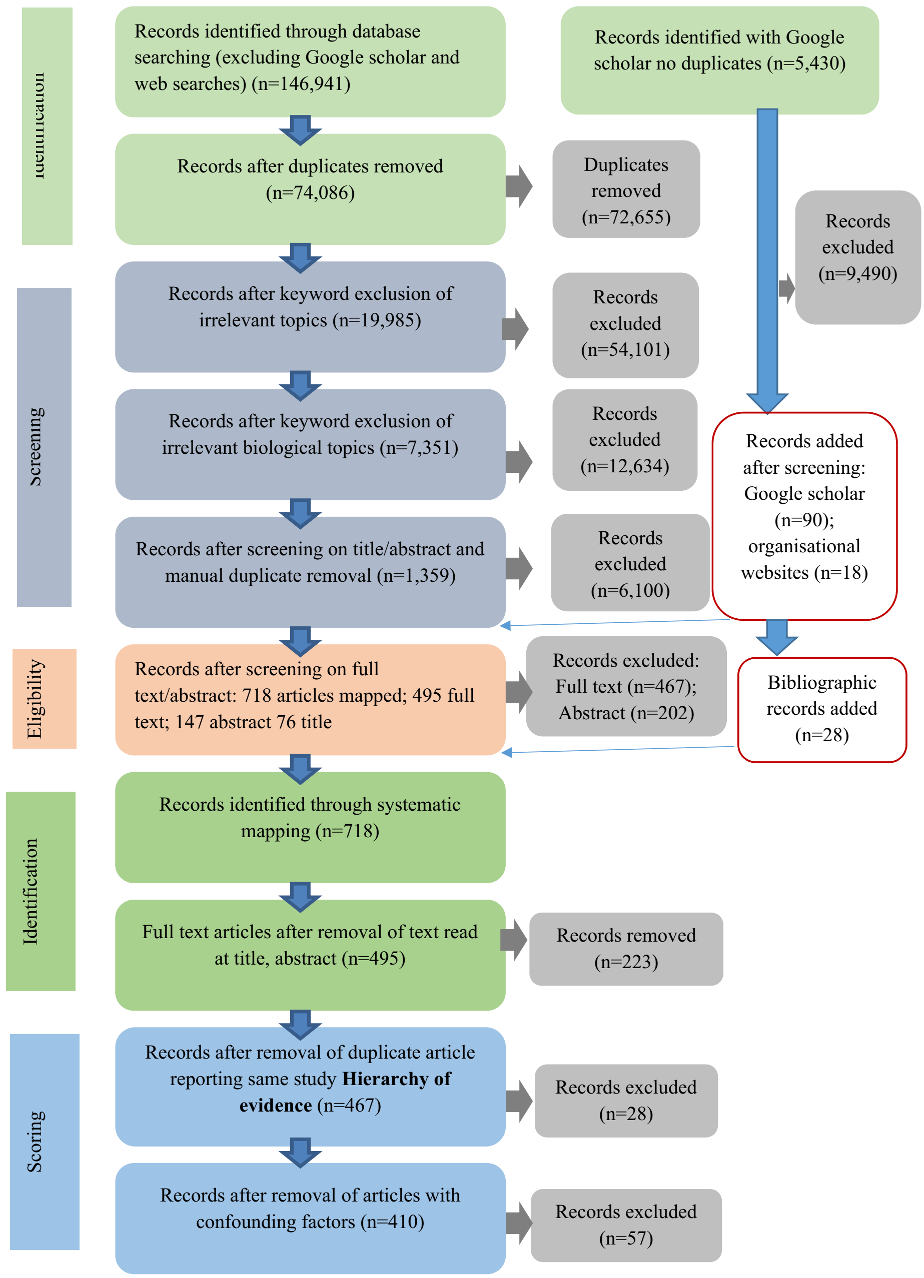

Fig. 1 Schematic of stages for the systematic map.

Study outcome

Overall, 36 pesticides and 7 types of FIO and 4 pathogens were included in the map. Eight different forms of N, and 10 forms of P were recorded. Four forms of sediment were recorded (see Additional file 3).

The dominant water quality outcome measured was N (n = 473), followed by P (n = 178) and sediment (n = 165). Less research was found for pesticides (n = 71) and FIOs or pathogens (n = 61). Most measurements of N were recorded in buffer strip (n = 209), cover/catch crop (n = 203) and slurry storage (n = 58) articles. Measurements of sediment were mainly reported in buffer strip articles (n = 128), although a few articles discussed cover/catch crops measuring sediments derived from soil erosion (n = 28). Likewise most articles that reported measurements of P were from buffer strips (n = 136), with less research found for slurry storage (n = 42) and cover/catch crops (n = 24). Pesticides were most often recorded in buffer strip articles (n = 63). Evidence for FIOs or pathogens was limited and came from articles reporting slurry storage (n = 34) and buffer strips (n = 32).

Study quality

Cover/catch crop studies had the highest scientific rigour values [mean value of 6.8, standard deviation (SD) 3.1] compared to buffer strip (mean 5.9, SD 2.4) and slurry storage studies (mean 4.1, SD 3.1). These values reflected that the majority of cover/catch crop and buffer strip studies were manipulative, often controlled and fully replicated, and were of longer duration compared to slurry storage studies. Furthermore, fewer buffer strip and slurry storage studies were randomised compared to cover/catch crop studies.

Study quality was not assessed for woodland creation and subsoiling studies due to the low number of studies found.

Buffer strips (including tree buffers)

Description of studies

Two hundred and twenty-five buffer strip studies were included in the database after studies with confounding factors and articles reporting the same study were removed. Almost two-thirds of the studies were conducted in the USA (n = 139), the rest were mostly from Europe (n = 62).

Buffer strip study design

Over half of the studies were manipulative (n = 148) with the remainder mainly correlative (n = 74). Approximately, half of the manipulative studies had temporal replication (n = 73) and most of the rest (n = 55) had times series data. The majority of the correlative studies were conducted for at least a year or longer (n = 52), whereas, over a third of manipulative studies were conducted for less than a year (n = 83). Very few buffer strip studies were conducted for longer than 10 years (n = 5).

One hundred and four studies had a control, most frequently bare ground (n = 38) or of cropped/alternative vegetation (n = 27). Only 1 study used a Before-After Control-Impact experiment. Studies without a control usually had a comparator (n = 121), often comparing water quality at different points along the width of a buffer, starting from the inflow of water and ending at the outflow (n = 82). Some controlled studies reported results in relation to inflow measurements rather than controls. Three studies measured changes in water quality over time.

Most of the studies were conducted at single sites/farms (n = 129) with fewer multi-site studies (n = 41), or larger scale studies at catchment, regional, country or international level (n = 38). Only twenty-three studies sampled river water, which may reflect the difficulty in eliminating the impact of confounding factors in river/catchment studies. Seventy-four studies had data for all 4 seasons, and more studies were conducted in summer (n = 62) than autumn (n = 21) or winter (n = 13). Recording of soil type was often varied or absent (n = 72) but most commonly fell within the loam range (n = 129).

Buffer strips were composed of either grass (n = 154), trees (n = 55) or a mixture of trees, grasses or shrubs (n = 69). More studies recorded buffer strips composed of deciduous trees (n = 80) than conifer species (n = 9). Vegetation manipulation was a common experimental factor e.g. species, density, cutting (n = 98). Other factors included type or amount of fertilizer applied to plots, buffer width and soil type.

Outcomes measured

One hundred and thirty-nine studies assessed the effectiveness of buffer strips for reducing N. Nitrate (n = 120) and ammonium (n = 46) were the most commonly measured forms of N. Nitrate was most often recorded in groundwater whilst ammonium was most often recorded in surface water (Fig. 2). Very few studies investigating organic forms (n = 10). Measurements of groundwater/subsurface flow were more common for woodland buffer studies (n = 39/52), than grass buffer studies (n = 14/102). Nitrate was commonly measured in both woodland and grass buffer strips but Total N and ammonium were more often measured in grass buffers (Fig. 3). Ninety-four studies assessed the effectiveness of buffer strips for reducing P. Total P and orthophosphate were the most commonly recorded measurements.

Studies most often measured P in surface waters (n = 50). Little research was found for P measured in subsurface (n = 5) or groundwaters (n = 13). This possibly reflects the properties of phosphorus, which has a low mobility in soil. Thirteen studies measured P in multiple flow paths. A total of 97 studies assessed the effectiveness of buffer strips for reducing sediment in water. The remaining studies measured sediment as 'sediment loss' and 'turbidity'.

Nineteen studies assessed the effectiveness of buffer strips for reducing FIOs or pathogens and the majority of these investigated surface flow (n = 17). Total faecal coliforms and *E. coli* were the commonest forms of FIO measured (Fig. 4).

Thirty-eight studies assessed the effectiveness of buffer strips for reducing pesticides in water, 15 measured pesticides in surface flow, 9 in subsurface flow and 8 in both flow paths.

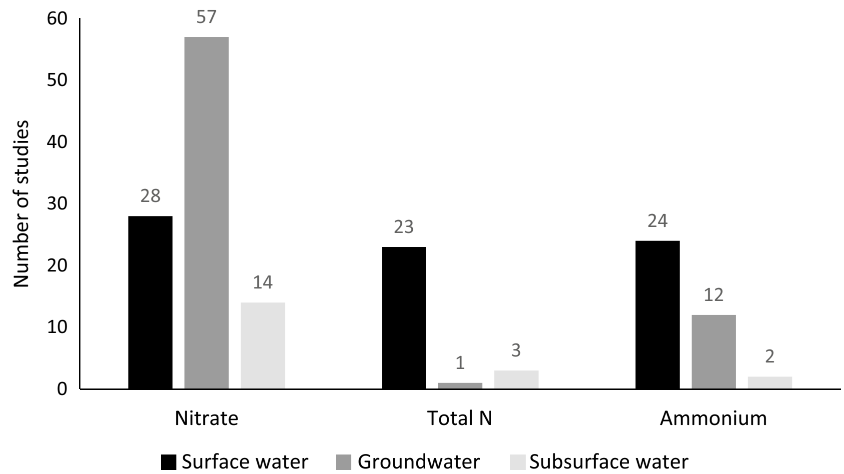

Fig. 2 Number of buffer strip studies measuring different forms of nitrogen (N) in surface, subsurface and ground waters. Studies with multiple flow paths or studies where flow paths were not clear were excluded. When flow path was not stated and measurements were taken below ground a default coding of subsurface was used, therefore the distinction between groundwater and subsurface may not be valid.

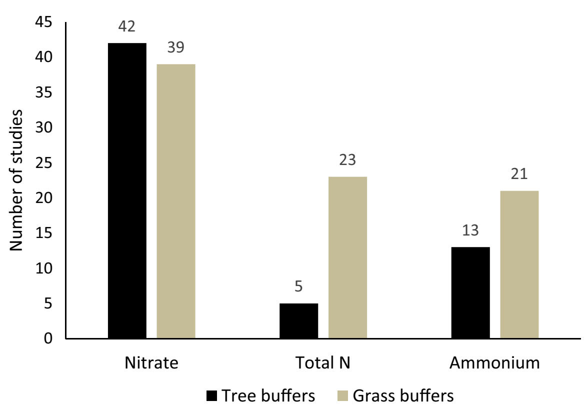

Fig. 3 Number of tree and grass buffer strip studies for each form of nitrogen (N) measured. Studies with multiple buffer types were excluded. Grass-shrub buffers were excluded. Tree buffer strips included tree; tree-grass; tree, grass, shrub; grass tree buffers. Studies where tree buffers were compared to grass buffers were excluded.

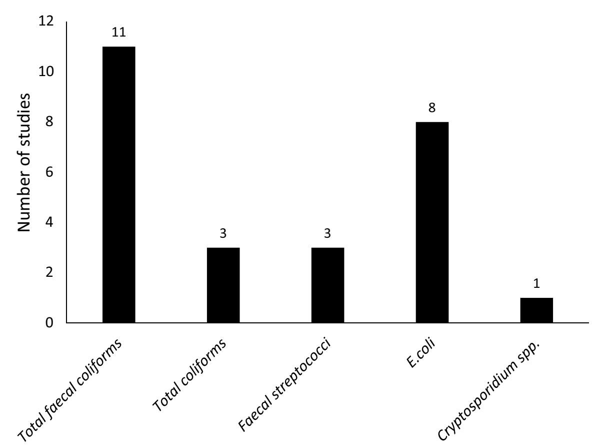

Fig. 4 Number of buffer strip studies for each form of faecal indicator organism or pathogen from faecal material measured.

Thirty-five different pesticides were investigated, with the herbicide atrazine (no longer approved for use in the European Union) the most commonly studied (n = 26).

Cover/catch crops

Description of studies

One hundred and thirty-two cover/catch crop studies were included in the database after studies with confounding factors and articles reporting the same study were removed. Over two-thirds of studies were conducted in European countries (n = 87; UK n = 18) and the majority of the remainder in the USA (n = 33).

Cover/catch crop study design

Studies were mainly manipulative (n = 125) with a few correlative studies (n = 6) and one monitoring study. Most studies were conducted for at least two winter seasons (n = 102) with 8 lasting for more than 10 years. Grass (n = 61) and cereals (n = 51) were the most commonly studied cover/catch crop and were either grown alone, intercropped with a winter crop, or drilled into the stubble left from the previous crop. Fallow, bare ground or cropped plots were commonly used controls. A few studies did not have a control, either measuring changes in water quality over time or between different cover/catch crop types. Volunteer weeds and winter wheat were sometimes used as controls, but in other cases used as crop covers.

The effectiveness of cover/crops in improving water quality was mainly measured from within field plots (n = 111). Only one study sampled river water [33]. Loam was the most commonly studied soil type (n = 71).

Commonly used experimental factors were crop type (n = 62), date and amount of fertilizer application (n = 45), the date and technique for removing the cover/catch crop (n = 6), type of tillage (n = 27) and soil type (n = 18).

Outcomes measured

No studies were found measuring FIOs or pathogens and only 3 studies measured pesticides Isofutole (n = 1); glyphosate (n = 1); metolachlor and atrazine (n = 1).

One hundred and fourteen studies assessed the effectiveness of cover/catch crops for reducing N, mainly from subsurface (n = 77) measurements. Grass (n = 55), cereal (n = 44), brassica (n = 30) and legumes (n = 28) were the most commonly studied cover/catch crops (Table 4). Nitrate was the most commonly measured form of N. No studies were found measuring organic forms of N.

Fourteen studies measured P most commonly in surface or subsurface flow on a range of soil types. Grass (n = 9) was the dominant cover/cover crop studied (Table 4). In some sediment studies, a crop cover of winter wheat rather than a traditional cover/catch crop was used. Most of the 19 cover/catch crops studies measuring sediment, studied grass (n = 8), winter wheat (n = 5) or other cereal (n = 6) on a loam soil type. The focus of a majority of the studies was erosion.

Slurry storage

Description of studies

Forty-two studies were included after studies with confounding factors and articles reporting the same study twice were removed. Over half the evidence was from outside Europe where slurry storage construction legislation may be different. For example, of the 23 studies that measured leakage of N, 17 were from the USA or Canada. Many studies (n = 20) also used earth lined stores which may not meet current legislation.

Table 4 Type and number of different cover/catch crops studied for reducing N, P and sediment

Cover/catch crop type	N	P	Sediment
Grass	55	9	8
Cereal	44	2	6
Crucifer	30	1	1
Legume	28	3	2
Other	3	0	1
Volunteer weeds	7	2	2
Winter wheat	12	2	5
Not clear	5	3	3

Numbers are from full text studies without confounding factors.

Study design

The 42 studies could be divided into 3 categories:

- Studies that measured leakage from under or nearby to slurry storage (n = 23). These types of studies were mainly correlative using measurements over time and distance as comparators. Slurry was normally sourced from swine or dairy farms. Most of the slurry stores studied were earth lined and below ground. Only 4 of the articles were less than 10 year old and only 6 of the studies were conducted in Europe (the other studies were from the USA and Canada). Slurry storage legislation and drinking water standards may therefore not be comparable across studies.
- Studies measuring survival rates of FIOs or pathogens in slurry, the comparator being time (n = 11).
- Field-based studies that measured the effect on water quality of timing and amounts of slurry application in winter following storage (n = 8).

Outcomes measured

Thirty studies measured N. Whilst N was often detected under or near slurry storage many of the studies were not of the highest scientific rigour often lacking baseline pre and post slurry storage water quality data. Most studies were conducted for less than 2 years, therefore the effect over time may not have been accurately assessed. Soil type has also been given as a reason for differences in slurry storage leakage.

Only a small amount of evidence was found for P (n = 10) spread across the different study types.

Eighteen studies measured FIOs or pathogens with eleven studies measuring survival rates of FIOs or pathogens in slurry.

Although timing of slurry application was not searched for, eight studies were found. However, experimental design and outcomes measured were variable.

Woodland creation (excluding woodland buffers)

Description of studies

Twelve woodland creation studies were found all from Europe with the exception of one study from Canada.

Study design

The studies could be divided into three main categories: (1) Studies measuring water quality under afforested former agricultural land, comparing results to cropped or forested land or measuring differences across different tree species. This included studies that reported findings from the AFFOREST project which measured the effect on water quality of afforestation on former agricultural soils in 3 different European countries [34]. (2) Studies measuring the effect on water quality over time of trees grown for biomass (3) Studies measuring the effect of water quality of trees intercropped with a cash crop.

Outcomes measured

Woodland creation studies most frequently measured N (n = 11), whereas P, sediment and FIOs were only measured once. The variety of controls/comparators employed in woodland creation studies made it difficult to code outcomes. Some afforestation studies did not have a non-woodland control, but instead measured changes in water quality over different aged woodlands making it difficult to be certain if woodland had improved water quality compared to agricultural land [35, 36]. Some biomass studies did not have a non-woodland control, but instead used a non-fertilized treatment as a control [37].

Modelling studies were excluded from the review. However, these studies are potentially useful as woodland experiments can take years to assess. The role of trees in pesticide drift reduction was not included in this review as pesticide was measured as a deposit rather than within water. Nisbet et al. recently reviewed the role of trees on water quality combining both woodland creation and buffer strip studies to provides a comprehensive review in this area [14].

Controlled traffic on grassland

No studies were found for controlled traffic on grassland.

Subsoiling

Description of studies

Only 5 studies were coded for subsoiling and these were all from outside of Europe (USA n = 4; Canada n = 1).

Study design and outcomes measured

All the studies were manipulative and used a no-subsoiling control. Four out of the 5 subsoiling studies measured soil erosion and sediment loss from plots and one studied N and P.

Discussion

Major findings

The majority of the evidence collated in this map investigated the effectiveness of buffer strips and cover crops for improving water quality. More than half of the buffer strip studies originated from the northern states of the USA, with the remainder of the evidence from Europe. The majority of buffer strip studies focussed on reducing N followed by sediment, P, pesticides and FIOs or pathogens.

More than half of the cover/catch crops studies were carried out in Europe where studies focussed predominantly on reducing N followed by fewer studies on sediment, P and pesticides. No studies were found for FIOs or pathogens.

The majority of the buffer strip and cover/catch crop studies were published in peer review journals and were of high rigour. However, much of this research is from field scale experiments and further research is needed to assess mitigation effectiveness at catchment scale. This research gap was also highlighted in a recent COST action knowledge exchange programme for buffer strips [38]. Studies of buffer strips and cover/catch crops were often of short duration and rarely recorded seasonal data. The majority of buffer strip studies included in this review were conducted only during the summer so the impact of rainfall events and mitigation effectiveness over time may not have been fully captured.

Fewer studies were found investigating the effectiveness of slurry storage for improving water quality, the evidence often lacked rigour and many of the slurry stores used in the studies did not meet current EU legislation and the studies were from outside of the EU where legislation on storage may be different. The evidence for woodland creation and subsoiling was very limited and no evidence was found for the effectiveness of controlled trafficking on grassland for improving water quality.

Limitations of the evidence base

Buffer strips

Buffer strip studies were usually carried out on either loam or unknown soil types, which may not capture the effect of soil particle size on buffer strip performance. One multi-site study, with silt loam, and silt clay loam soils [39] noted that a wider buffer was needed for soils with a high clay content as soil particles were smaller and took longer to deposit in surface flow.

Buffer strip effectiveness was often assessed at field scale, which may not capture the effects of preferential flow paths or buffer strip placement on buffer strip performance. A Defra commissioned buffer strip study at three sites representative of UK soil types [40] found no significant difference in levels of total-N, nitrate or molybdate reactive P in river samples taken from paired catchments (buffered and not). However, at the field site fans of sediment deposits were observed at the edge of the buffer strip and ground monitoring wells recorded reductions in nitrate and total N on buffer strip sites (not clear for P). One explanation given for the result was that phosphate could have been stored as sediment in the river and was acting as a source for sediment bound

P which, until depleted, would mask any positive effects of buffer strip implementation. Another reason cited was that water flows may have bypassed the buffer strip either through underground drainage, or vertical movement into aquifers. Reductions in P measured at buffer strip plots not translating to reductions in stream samples have been observed in other studies [41]. The authors suggested that the study should have been longer than 2 years to observe the long term effectiveness of buffer strips. Variation in the effectiveness of buffer strips over time has also been noted in other studies [42, 43]. Differences between vegetation types such as grass and trees may only become apparent over time, as trees mature more slowly.

Variability in the hydrological landscape has been cited as an important factor for buffer strip effectiveness for leaching of N [44].

Seasonal differences in plant growth and nutrient uptake may impact on buffer strip effectiveness. Further analysis of the studies with data for all four seasons would be needed to identify any seasonal effect.

Cover crops

Authors have suggested that a number of factors can impact on the effectiveness of cover/catch crops such as the amount of fertiliser applied, the crop rotation and crop or cover/catch crop type.

Climatic data was often difficult to extract from studies, however some studies reported year to year variation in effectiveness depending upon the date when autumn rains started [12]. Only a quarter of the studies assessed effectiveness across all four seasons. However, a study reported in two articles cautioned that cover/catch crop effectiveness in reducing leaching of N should be assessed over the full crop succession [45, 46]. Although some studies were of long duration (up to 30 years), the impact of stopping cover/catch cropping was only investigated in a few studies e.g. [47–49].

The only cover/catch crop study in the map that measured water quality in stream/river samples was a long term catchment monitoring study (9–16 years) [49]. Cover/catch crop studies were often conducted on loam or unknown soil types, which may not capture differences between soil types and nutrient leaching (e.g. sandy soils).

Slurry storage

Most of the evidence for slurry storage related to studies measuring leakage from slurry stores, particularly for N and P. Many of the slurry storage studies were from outside of Europe, over 12 years old and used earth lined slurry stores and were therefore not relevant to current UK legislation.

Scientific rigour for slurry storage studies was variable with authors often suggesting results should be interpreted with caution. For example, spraying of slurry on adjacent fields may have contaminated water sources, rather than the slurry storage unit. Furthermore, many studies had confounding factors as they were part of catchment studies, highlighting the difficulty in measuring water quality within river systems.

In addition to the studies that examined leakage from slurry stores or reductions in FIOs in stored slurry, a few studies were also found that related to the timing of slurry application, even though this had not specifically been searched for. The timing of slurry application is an important consideration in current Nitrate Vulnerable Zone (NVZ) regulations in the UK, and a separate Rapid Evidence Assessment (REA) was subsequently commissioned and carried out regarding the alteration of timing to slurry application on water quality [50].

Strengths and limitations of the review

Limitations of the search

Non English language search terms were excluded. However, over 100 articles in the map were assumed to be non-English language texts and included on titles/abstracts. Their translation would extend the evidence base. For example, some woodland creation reports, written in French or German, were not coded on full text [51, 52]. Although web searches were conducted for a variety of organisations, grey literature may be under-represented, where it is not available online. Some included studies contained forms of the interventions that were not specifically searched for (e.g. winter wheat to provide a crop cover). These topics may be less comprehensively covered in the database.

Limitations of the systematic map

Articles lacking full text were coded on title and abstract which may result in the inclusion of some non-relevant studies. Only studies that demonstrated a direct effect of the intervention on water quality were included in the map, thereby excluding studies that measured indirect (but important) effects such as soil water infiltration, crop yields, soil mineralization rates, and herbicide degradation. Furthermore, only overall outcomes were recorded for a study therefore differences in sampling location, mitigation, study site, and flow path were not captured.

Limitations in hierarchy of evidence

The standard values that were applied to all studies may have excluded important water quality specific or experimental design factors that were not considered. Furthermore, many related factors (such as the potential for pollution swapping) have not been considered by this work.

Review conclusions

Implications for policy/practice

This systematic map documents and categorise all available evidence on the effectiveness of buffer strips, cover/catch crops, slurry storage, subsoiling, woodland creation and controlled trafficking on grassland to improve water quality in terms of N, P, sediment, pesticides, FIOs and pathogens from faecal material. The map provides a useful output for decision makers to extract evidence on more specific areas of the topic. It can be used to highlight evidence gaps to direct future research funding and identify where there is sufficient evidence to answer specific questions using systematic review (see implications for research).This map has specifically highlighted that:

- The evidence base for slurry storage and effect on surrounding water quality is dated and may not relate to current/regional legislation.
- Evidence for woodland creation, subsoiling and controlled trafficking on grassland, on water quality is limited or lacking.

The systematic map provides a large database of research that can be used to filter information by mitigation, water quality measurement or experimental factor e.g. buffer width. This map could be of use to decision makers and delivery agencies to better facilitate catchment planning as required under the water framework directive [53–55].

Study outcomes for the effectiveness of some interventions for specific pollutants are recorded in the searchable database as outlined in the a priori protocol, but the findings are not synthesised in this systematic map. These are summarised in a report to Defra [56] and in an accompanying policy distillation [57].

Implications for research

This systematic map can be used to help identify cases where there may be sufficient data on a specific question to justify a systematic review and identify evidence gaps for future primary research.

Priorities for primary research

Reporting of the primary research was variable, and improved reporting should be a priority for researchers. Standard reporting of statistics in water related studies and submission of data with journal papers would increase the value of reported data, facilitate the reapplication of data to subsequent analyses and ensure that water quality data is not lost to science. In addition to this issue, the following key knowledge gaps were identified:

- There was very little research investigating the impact of subsoiling, controlled trafficking on grassland or woodland creation on water quality.
- Few studies measured the effectiveness of interventions at catchment scale.
- Further, long term studies with controls, pre and post water quality measurements and multiple sampling points from both field and rivers would improve the evidence base.
- Further research investigating seasonal variations in the effectiveness of interventions, particularly buffer strips, woodland creation and cover/catch crops would also be useful.

Knowledge gaps specific to the use of buffer strips

- There was limited research investigating the effectiveness of buffer strips for reducing leaching of organic forms of N or P, or for pesticides that are currently authorised for use/commonly used in UK agriculture.
- An evidence gap exists for the impact of cover/catch crops in reducing leaching of pesticides, FIOs and pathogens, and for organic forms of N and P.

Potential systematic review topics

Evidence in the map often had a general inconsistency in approach that would make meta-analysis challenging for some interventions, for example slurry storage and woodland creation. The evidence base for cover/catch crop and buffer strips was more comprehensive and consistent and studies were of a higher scientific rigour compared to the other interventions investigated in this map and are more likely to be suitable for meta-analysis. Potential systematic review topics for these two interventions could include:

Cover/catch crops

- The effect of time on the effectiveness of cover/catch crops.
- The interaction between cover/catch crops and applications of nitrogen and tillage.
- The effect of cover/catch crops compared to a cropped control (winter crop).

Buffer strips

There are some pre-existing meta-analyses which measured changes in levels of sediments, N, P and pesticides [17, 23, 32] as measured along the length of a buffer strip (comparing inflow/outflow) suggesting good potential for future systematic review. Other potential topics include:

- The effect of time on the effectiveness of buffer strips.
- The effect of pollutant solubility on mitigation effectiveness e.g. P.
- The effect of buffer strips compared to a cropped or bare ground control.
- Further research is also needed to capture the effects of preferential flow paths, buffer strip placement and buffer vegetation type on efficacy in order to maximise the effectiveness of buffer strips.

Additional files

Additional file 1: Spread sheet containing the exact search terms used.

Additional file 2: Coding categories used in the systematic map.

Additional file 3: Access database of coded review evidence searchable by category.

Authors' contributions

NPR, PLJ and LMD conceived and planned the systematic map. PLJ provided guidance on environmental quality and protection, and was a subject expert for buffer strips and slurry storage. LMD undertook the systematic map. NPR provided advice for systematic map activities. KJ and NPR wrote the manuscript. All authors read and approved the final manuscript.

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Whilst we consider that this work has been carried out in accordance with good industry practice, the University will not be liable for any use which may be made, reliance which may be placed, nor advice or information given, in connection with the results contained herein for commercial purposes.

Compliance with ethical guidelines

Competing interests

The authors declare that they have no competing interests.

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