Qualitative Impact Assessment of Land Management Interventions on Ecosystem Services ("QEIA")

Report-3 Theme-4: Water

30-June-2023

Qualitative impact assessment of land management interventions on Ecosystem Services

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This report is one of a set of reviews by theme:

Braban, C.F., Nemitz, E., Drewer, J. (2023). *Qualitative impact assessment of land management interventions on Ecosystem Services ("QEIA").* Report-3 Theme-1: Air Quality (Defra ECM_62324/UKCEH 08044)

Birnie, J., Magowan, E., Law, R., Lucas, O.T., Hassin, A.E.J. (2023). *Qualitative impact assessment of land management interventions on Ecosystem Services ("QEIA").* Report-3 Theme-2: Greenhouse Gases (GHG) (Defra ECM_62324/UKCEH 08044)

Newell Price, J.P., Williams, A.P., Bentley L. & Williams, J.R. (2023). *Qualitative impact assessment of land management interventions on Ecosystem Services ("QEIA")*. Report-3 Theme-3: Soils (Defra ECM_62324/UKCEH 08044)

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Staley, J.T., Botham, M.S., Broughton, R.K., Carvell, C., Pywell, R.F., Wagner, M. & Woodcock, B.A. (2023). *Qualitative impact assessment of land management interventions on Ecosystem Services ("QEIA")*. Report-3 Theme-5A: Biodiversity - Cropland (Defra ECM_62324/UKCEH 08044)

Keenleyside, C.B. & Costa Domingo, G. (2023). *Qualitative impact assessment of land management interventions on Ecosystem Services ("QEIA")*. Report-3 Theme-5B: Biodiversity - Grassland (Defra ECM_62324/UKCEH 08044)

Maskell, L. & Norton, L. (2023). *Qualitative impact assessment of land management interventions on Ecosystem Services ("QEIA")*. Report-3 Theme-5C: Biodiversity - Semi-Natural Habitats (Defra ECM_62324/UKCEH 08044)

Siriwardena, G.M. (2023). *Qualitative impact assessment of land management interventions on Ecosystem Services ("QEIA")*. Report-3 Theme-5D: Biodiversity - Integrated System-Based Actions (Defra ECM_62324/UKCEH 08044)

Bentley, L., Feeney, C., Matthews, R., Evans, C.D., Garbutt, R.A., Thomson, A. & Emmett, B.A. (2023). *Qualitative impact assessment of land management interventions on Ecosystem Services ("QEIA")*. Report-3 Theme-6: Carbon Sequestration (Defra ECM_62324/UKCEH 08044)

Short, C., Dwyer, J., Fletcher, D., Gaskell P., Goodenough, A., Urquhart, J., McGowan, A.J., Jones, L. & Emmett, B.A. (2023). *Qualitative impact assessment of land management interventions on Ecosystem Services ("QEIA")*. Report-3.7: Cultural Services (Defra ECM_62324/UKCEH 08044)

A list of all references used in the reports is also available as a separate database.

Foreword

The focus of this project was to provide a rapid qualitative assessment of land management interventions on Ecosystem Services (ES) proposed for inclusion in Environmental Land Management (ELM) schemes. This involved a review of the current evidence base by ten expert teams drawn from the independent research community in a consistent series of ten Evidence Reviews. These reviews were undertaken rapidly at Defra's request and together captured more than 2000 individual sources of evidence. These reviews were then used to inform an Integrated Assessment (IA) to provide a more accessible summary of these evidence reviews with a focus on capturing the actions with the greatest potential magnitude of change for the intended ES and their potential co-benefits and trade-offs across the Ecosystem Services and Ecosystem Services Indicators.

The final IA table captured scores for 741 actions across 8 Themes, 33 ES and 53 ES-indicators. This produced a total possible matrix of 39,273 scores. It should be noted that this piece of work is just one element of the wider underpinning work Defra has commissioned to support the development of the ELM schemes. The project was carried out in two phases with the environmental and provisioning services commissioned in Phase 1 and cultural and regulatory services in a follow-on Phase 2.

Due to the urgency of the need for these evidence reviews, there was insufficient time for systematic reviews and therefore the reviews relied on the knowledge of the team of the peer reviewed and grey literature with some rapid additional checking of recent reports and papers. This limitation of the review process was clearly explained and understood by Defra. The review presented here is one of the ten evidence reviews which informed the IA.

Acknowledgments

This project work and the resultant reports and databases were made possible by funding from the Department of Environment, Food and Rural Affairs, under contract ECM_62324. UKCEH and all the project participants are very grateful for the support we have received from DEFRA colleagues. In particular we would like to thank Tracie Evans, Hayden Martin, Daryl Hughes, Chris Beedie and Catherine Klein for their support and constructive inputs to the exercise. We would also like to thank our numerous external contributors and reviewers, some of whom have chosen to remain behind the scenes, and we are very grateful for the expansive and meticulous body of peer-reviewed evidence our authors have been able to refer to and make use of.

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INDEX OF ACTION CODES IN THIS REPORT

1 INTRODUCTION

Defra have commissioned a UKCEH-led consortium to assess the evidence base to inform the priority actions which should be considered for future land management policy. This work provides the logic and evidence to support land management actions using a rapid, expert approach. The objectives of this short project were to provide an evidence-based rapid expert assessment of the impact of land management actions, currently under consideration for inclusion in Environmental Land Management (ELM) schemes on ecosystem services and to highlight key considerations which are important for determining which actions should be included in future land management schemes (e.g. displacement risk, spatial variables, etc.).

This report describes actions that were considered to have on water quality, flow and resources. Actions that have similar outcomes have been group together in the following categories:

- Reducing nutrient inputs
- Nutrient management planning
- Manure management planning
- Preventing livestock access to watercourses
- Cover cropping and soil protection
- Sheep dip management
- Buffer strips
- Habitat creation – Wetland features
- Restoration, management and enhancement– River restoration
- Restoration, management and enhancement– Water level, dam maintenance

2 OUTCOMES

Primary outcomes the theme will review and assess (related to Ecosystem Services) are:

Theme	**Service**	**Indicator**
Water	[River/Flood?] Flow variability	tbd
	Control of river erosion	tbd
	Flood protection	Improved regulation of flow regime for peak events
	Flood protection	Reduced inundation from coastal flooding
	Resilience to drought	Frequency of low flow
	Water Quality	Improved ecological and chemical (bacterial, viral and suspended sediment) quality of Coastal
	Water Quality	Improved ecological and chemical (bacterial, viral and suspended sediment) quality of fresh water
	Water Supply	Increased water supply for non-drinking purposes

3 MANAGEMENT BUNDLES

3.1 REDUCING NUTRIENT INPUTS

3.1.1 ECPW-171; ECPW-173; ECPW-180; ETPW-239

ECPW-171	Use very low inputs on permanent grassland
ECPW-173	Use no fertiliser
ECPW-180	Whole farm reduction in nutrient use / nutrient cap
ETPW-239	Increase production from grass grazing and forage and reduce compound feed to reduce nutrient inputs

3.1.1.1 Causality

The build-up of surplus nutrients in excess of immediate crop requirement can lead to increased water and air pollution as well as reduce farm profitability (OECD, 2022). These actions limit nutrient inputs to land which will reduce the risk of excess nutrient application and the amount of residual nitrate and phosphorus in soil. There will be no effect on mineralisation of organic nitrogen which makes a significant contribution to nitrate leaching losses, especially in arable systems.

Most agricultural soils require applications of nitrogen from fertiliser and/or organic materials on an annual basis to ensure optimum crop growth. Most of the mineral nitrogen in the soil is present as nitrate, which is mobile in the soil. Any nitrate that is present in the soil at the start of the winter is unlikely to be taken up by crops as growth slows due to cold temperatures and reduced light intensity. When excess winter rainfall occurs, and water drains through the soil the nitrate is at risk of being lost from the soil by leaching.

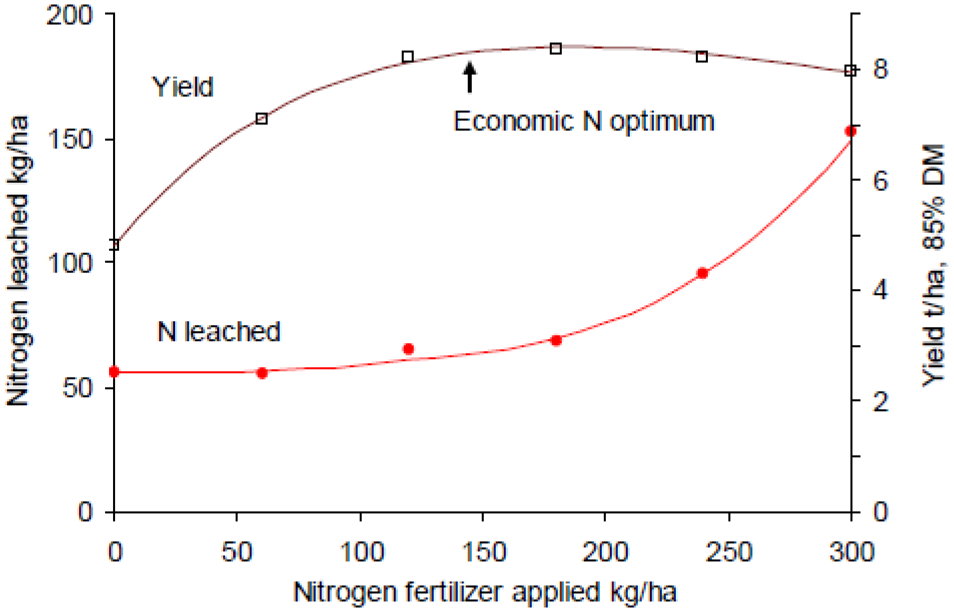


Figure 1. Impact of manufactured fertiliser nitrogen applications on winter wheat yields and nitrate leaching losses (Lord and Mitchell, 1998).

Nitrogen applications to arable crops that supply less than the economic optimum will result in sub-optimal crop yields and quality whilst applications that exceed crop requirement will increase the risk of nitrate leaching (Figure 1; Lord and Mitchell, 1998).

The extent to which soil is saturated with P will influence the risk of P losses to water. The soil saturation capacity depends on the quantities and forms of Fe, Al and Ca present in the soil and P is more strongly bound in the order Fe>Al>Ca (Withers, 2011). Risks of P loss to water have been reported to greatly increase once P saturation exceeds a threshold of 20-30% (Heckrath *et al*., 1995, Kleinman *et al*., 2000; Nair *et al*., 2004). P saturation threshold broadly equates to Olsen soil P indices of 3, 4 and 5 for sand, loam and clay soils, respectively. Consequently, soils with P indices above these levels represent an increased risk of P losses to water.

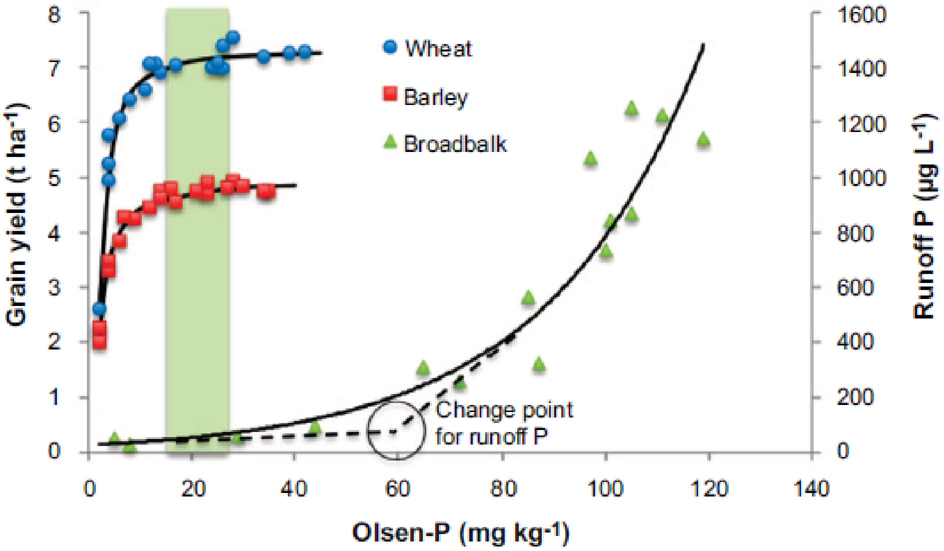


Figure 2. The impact of Olsen extractable P levels on crop yields and soluble P losses to water (Poulton et al., 2013, Heckrath et al., 1995). Graph taken from Withers et al., (2017).

Maintaining optimum soil pH for the farming system is crucial to ensure nutrients supplied are available for crop uptake. On mineral soils, low pH restricts P, Mg and Ca availability which reduces yields and increases risk of water pollution as N applied in fertilisers and manures is less likely to be taken up by crops. AHDB's Nutrient Management Guide recommends maintaining soil pH at 6.5 in arable systems and 6.0 on grassland by applying lime or lime base products.

3.1.1.2 Co-Benefits and Trade-offs

Reductions in fertiliser nitrogen inputs will reduce the risk of nitrous oxide and ammonia emissions from soils (Cardenas et al., 2010). There would also be a significant impact on crop yields (other than legumes). For example, a 20% reduction in fertiliser N use (below the economic optimum rate) would typically result in a 2-10% reduction in crop yields. A complete cessation of nitrogen fertiliser use on arable crops will typically lead to halving of crop yields. Initially, the impact of reducing fertiliser P use would be greatest for responsive crops (e.g. potatoes and some vegetable crops). It is important that any reduction in fertiliser use should take account of the interactions between nutrients and not create an imbalance in the soil. A shortage of one nutrient may limit uptake of another and potentially increase losses of the second nutrient.

[TOCB Report-3-2 GHG ECPW-171] Benefits of low inputs on permanent grassland can include increased range of plant species and a reduction in emissions due to reduced inputs of artificial fertiliser. Trade-offs include lower output per hectare and an increased landmass per unit of livestock. However, these benefits do not always accrue and are dependent on a range of other factors being in place.

[TOCB Report-3-5D Systems **ECPW-180**] Whole farm reduction in nutrient use / nutrient cap
This is a general nutrient management action, from which we expect an overall reduction in nutrient inputs, with various positive effects on WQ and biodiversity. At the whole-farm level, these could be quite significant. However, effects will depend on the context of baseline nutrient levels.

[TOCB Report-3-5D Systems **ETPW-239**] Increase production from grass grazing and forage and reduce compound feed to reduce nutrient inputs It is not clear how this would achieved, as an increase in production from grass implies either more land under grass or more intensive grass production, albeit with reduced displacement of these production needs to locations that produce the compound feed. Local negatives for biodiversity would be expected, but potentially compensated for by positives elsewhere.

3.1.1.3 Magnitude

The magnitude of the reduction of nitrate and phosphorus losses to water will depend on the scale of reduction in nutrient inputs and the soil nutrient status. Reductions in fertiliser N use of c. 20% from current economic optima may be expected to reduce nitrate leaching losses by 5-10% (Newell-Price et al., 2011). A complete cessation of fertiliser N inputs to non-leguminous arable crops would be expected to reduce nitrate leaching losses by over 50% compared with current levels. On grassland, it is likely that reductions in fertiliser and concentrate use will result in reduced stocking rates which will reduce the risk of nitrate leaching losses from manure applications and grazing returns. However, the use of clover and mixed swards may lead to increased nitrate leaching due to the need for reseeding to maximise sward productivity. Reductions in P fertiliser use are likely to have the biggest impact on soils that are saturated with P (i.e. at soil index 4-5 and above). It would be expected that soluble P losses would be reduced by up to 10% (from a 20% reduction in P fertiliser rates) plus longer-term reductions through reduced soil P status.

3.1.1.4 Timescale

Nitrate leaching losses will be reduced within 1-2 years. Limiting P fertiliser applications in any one year will reduce the amount of soluble P at risk of loss in surface runoff or drainflow and in the longer-term (where soil P reserves have run down) there will be a reduction in both soluble and particulate P losses. However, where soil P levels are high it is likely to take several years (decades) for soluble P concentrations to drop to reduce P loss to low levels (Newell-Price et al., 2011).

3.1.1.5 Spatial Issues

These methods have the potential to be applied at across all agricultural land and production systems that use manufactured fertiliser and concentrated feeds i.e. high output arable farms as well as intensive dairy and beef enterprises.

3.1.1.6 Displacement

Reducing fertiliser inputs is likely to lead to significant reductions in crop yields. Reducing concentrate use on livestock farms are also likely to result in reductions in meat and milk production.

3.1.1.7 Maintenance and Longevity

It is likely that small reductions in nutrient inputs will require little change to farm management. However, where nutrient inputs are reduced significantly it will be necessary to use fertility building techniques, such as introducing grass and clover leys in arable rotations to support crop yields. Timing of destruction of the leys will be important to minimise the risk of nitrate leaching and sediment losses.

3.1.1.8 Climate Adaptation or Mitigation

Reduction in manufactured fertiliser use will lead to reductions in the GHG emissions associated with manufacture fertiliser production (Bentrup et al, 2018). However, reductions in crop yield may lead to the need to import food which may come from parts of the world where the GHG production per unit of production is greater than in the UK. However, where soil P levels are high it is likely to take several years (decades) for concentrations to drop sufficiently to reduce P loss in the UK.

3.1.1.9 Climate Factors / Constraints

Changes to crop rotation that may be required to adapt to reductions in fertiliser (e.g. fertility building, increased use of legumes etc) may be limited by soil type and climate interactions (e.g. spring cropping may not be possible on heavy textured soils.

3.1.1.10 Benefits and Trade-offs to Farmer/Land manager

Whilst reductions in livestock production from reduced use of feed concentrates and in crop yields from reduced fertiliser inputs will be balanced by reductions in farm input costs, it is likely that farm productivity and income will be significantly reduced. On arable farms, if production levels are to be maintained then changes in farm management, including the use of fertility building crops such grass clover leys, will be required. On livestock systems a greater reliance on grass feed may require investment in infrastructure, such as concrete yards and silage clamps and effluent collection to store feed safely.

3.1.1.11 Barriers to Uptake

Reducing fertiliser and concentrate use by small amounts are likely to have only small impacts on farm productivity. However, significant reductions in nutrient use are likely to require changes to farm production systems and business models which may require investment in equipment, adopting new skills and increased commodity prices reflecting lower levels of production.

3.1.1.12 Other Notes

None

3.2 NUTRIENT MANAGEMENT PLANNING

3.2.1 ECCM-004; ECPW-106

ECCM-004	Nutrient Management Plan
ECPW-106	Target application of fertiliser (time, location, soil type, environment, weather at time of application and afterwards) to match crop need and minimise losses

3.2.1.1 Causality

These actions require using a recognised fertiliser recommendation system (e.g. Agriculture and Horticulture Development Board's Nutrient Management Guide (RB209), PLANET, MANNER-*NPK* and other supplementary guidance) to plan nutrient applications to all crops so that optimum rates for crop production are not exceeded. The plan should also include timings for fertiliser and manure applications to minimise the risk of nutrient losses (e.g. avoid autumn N use and manage early spring applications to drained soils) to water.

A good fertiliser recommendation system ensures that the necessary quantities of nutrients are available when required for uptake by the crop. Nutrients are only applied when the supply of nutrients from all other sources is insufficient to meet crop requirements. As a result, the amount of excess nutrients in the soil is reduced to a minimum. Use of a recommendation system should also ensure that the soil is in a sufficiently fertile state to maximise the efficient use of nutrients already in the soil or supplied from other sources, such as fertilisers/organic manures. Maintaining soil pH and an appropriate balance between different nutrients (i.e. NPKS) is also important to maximise the efficient uptake of al nutrients and reduce environmental losses to a minimum.

3.2.1.2 Co-Benefits and Trade-offs

Ensuring optimum nitrogen supply will reduce the risk of excess soil nitrogen which will reduce the risk of nitrous oxide and ammonia emissions to air. Where a plan results in reductions in manufactured fertiliser, N and P use will reduce the overall carbon footprint of crop production by reducing the GHG emissions associated with fertiliser production (Bentrup et al.,2018). Where insufficient nutrients have been applied to support optimum crop yields, nutrient applications from fertilisers and manures may increase leading to enhanced crop yields. Under this scenario it is likely that the environmental losses per unit of production will reduce, however the total nutrient losses (e.g. nitrous oxide emissions to air following elevated fertiliser N applications) may increase.

On livestock farms matching nutrient supply in animal feeds to achieve optimal livestock production (i.e. not over-feeding protein, which is degraded into nitrogenous compounds in livestock excreta) may lead to reduced nitrogen loadings and reductions in ammonia and nitrous oxide emissions from livestock housing and manure storage and following manure application to land.

3.2.1.3 Magnitude

Information from the England Farm Practices Survey (2019) suggests that 58% of agricultural holdings covering 73% of the farmed area had nutrient management plans.

Newell Price *et al.,* (2011) suggested that the use of fertiliser recommendation systems had the potential to reduce nitrogen and phosphorus losses to water and ammonia and nitrous oxide emissions to air by c.5%. The impact would depend on the current level of nutrient use and the extent to which manure nutrients were being accounted for when planning manufactured fertiliser applications.

Data from the British Survey of Fertiliser Practice (2018) indicate 88% of tillage land and 52% of grassland in England and Wales received applications of manufactured fertiliser nitrogen in 2017. Average field rates for tillage land were 159 kg/ha N compared with 98 kg/ha on grass. Fertiliser phosphate was applied to 44% of tillage land and 30% of grassland in England and Wales with average field rates of 59 kg/ha P_2O_5 on tillage land and 22 kg/ha P_2O_5 on grassland, respectively. An estimated 34% of grassland and 22% of tillage land in England and Wales received applications of organic manure in 2017.

3.2.1.4 Timescale

Where nutrient management planning results in improved timing of manure applications and prevents excess soil nitrogen supply reductions in nitrate leaching should occur within 1 -2 growing seasons. Reductions in phosphorous losses will occur when excess soil P levels have reduced sufficiently which is likely to take several years depending on soil type and crop rotation (Newell-Price et al., 2011).

3.2.1.5 Spatial Issues

Nutrient management planning will be most effective on all farms where manufactured fertilisers and organic materials are applied to land regularly to support crop yields. These farms are likely to include dairy, specialist beef, specialist sheep, arable and horticulture production systems. In high output systems, effective nutrient management is essential to underpin economic performance. In these systems, replacing nutrients taken off by crops with manufactured fertiliser or applications of organic materials (e.g. livestock manures, biosolids, compost, digestate etc.) is essential to maintain optimum crop yields and quality.

In extensive systems (e.g. upland beef and sheep enterprises) and on land where yield potentials are limited by factors such as climate, soil depth and topography (e.g. Agriculture Land Classification groups 4 and 5), detailed nutrient management planning will be less important to farm productivity.

3.2.1.6 Displacement

Improving utilisation of manure nutrients will reduce the need for manufactured fertiliser inputs to optimise crop available nutrient supply. Reductions in fertiliser N use will reduce the need for energy intensive fertiliser production and reductions in fertiliser P use will reduce the need for imports of phosphate fertilisers produced from finite resources of rock phosphate.

3.2.1.7 Maintenance and longevity

Nutrient management planning requires access to decision support systems that provide guidance on crop nutrient requirement, fertiliser application rates based on soil analysis and information on the crop available nutrient supply from manure applications. Regular soil sampling (at least every 5 years) will be required to ensure soil pH and P, K and Mg contents are maintained. Manure analysis to quantify manure nutrient supply will also be required. Investment in advisory services to train and support farmers to improve nutrient management is required

3.2.1.8 Climate Adaptation or Mitigation

Climate change may lead to changes in growing season, yield potentials and cropping patterns etc. It will be important to update recommendation systems to adapt to changing growing conditions.

3.2.1.9 Climate factors/constraints

None.

3.2.1.10 Benefits and Trade-offs to Farmer/Land manager

Savings in fertiliser use, as a result of identifying excess nutrient applications, will improve farm profitability by reducing inputs and potentially by increasing crop yields and quality. Where insufficient nutrients have been applied for optimal crop growth, increased fertiliser use will increase crop yields. It is necessary to a have nutrient management plan based on soil analysis and crop requirement to comply with the Farming Rules for Water in England (Defra, 2021). There would also be a benefit from better WQ and living in a less polluted environment.

3.2.1.11 Barriers to uptake

The requirement to keep records, sample and analyse soils and manures and use decision support tools to draft nutrient management plans will inevitably add direct and staff costs to farm businesses. Training to understand the factors controlling nutrient management decisions and the complexities of fertiliser recommendation systems is essential (e.g. via the BASIS FACTS scheme). A certain level of computer skills and the ability to access information from the internet is required to produce nutrient management plans using some decision support tools. It is important that computer based nutrient management tools are updated for compatibility with current software and hardware.

3.2.1.12 Other Notes

None

3.3 MANURE MANAGEMENT

3.3.1 ECPW-137: Export manure and slurry

3.3.1.1 Causality

Nutrients in livestock manures (i.e. cattle and pig Farm Yard Manure and slurry, poultry manure) are removed and exported to neighbouring farms. This reduces the nutrient load on the exporting farm and thereby reduces the risk of diffuse pollution from that farm. The export of manure should also enable the remaining manure to be managed in a more integrated way i.e. there will be less pressure to spread manures during high-risk periods and to better time applications in relation to crop demand.

3.3.1.2 Co-Benefits and trade-offs

Crop available nutrient supply from the manures will reduce the need for manufactured fertiliser inputs to meet optimum crop requirements on the receiving farm. On arable soils, the addition of organic matter from the manures has the potential to improve soil quality.

Manure storage and application equipment will be required on the receiving farm to ensure manure applications are made at appropriate timings and rates.

[TOCB Report-3-2 GHG **ECPW-137**] Benefits of exporting manure and slurry include the reduction of GHG to the atmosphere and excess nutrients to water, provided that the slurry is exported to an area which can make more effective use of it. The export of surplus nutrients to an appropriate region will optimise nutrient use, displace chemical fertilisers, and decrease the environmental impact. In addition to greenhouse gas reductions, other benefits around reduction of nutrient loading of land will accrue. Based on average values of N content of raw slurry at 7% DM, the export of 500 t of raw slurry off farm with a P_2O_5 content of 300 kg. If the same amount of N is exported in separated slurry solids, 189 t of solids would have to be exported containing 378 kg of P_2O_5 (Lyons et al., 2021). If, however, the slurry is moved to an area which cannot make more effective use of it than the farm of origin, benefits will be seen locally to the farm of origin, but negative impacts are likely locally to the receiving farm and catchment. Trade-offs centre around the cost of storage and transport of excess nutrients, as well as the risk of spillage during transport.

3.3.1.3 Magnitude

The magnitude of reduction in nitrate and phosphorus losses to water on the exporting farm will depend on the quantity of manure exported and on the impact manure exports have on the timing of manure application. If the reduction in manure volumes results in spring application timings on both exporting and receiving farms, then the risk of nitrate leaching losses will be reduced by up to 60% (Bhogal et al., 2021). However, if applications are made to wet soils then the risk of phosphorus loss from manure applications will increase.

3.3.1.4 Timescale

Nitrate leaching losses on the exporting farm will be reduced within 1-2 years. Phosphorus losses will be reduced in the longer-term as soil P reserves decline.

3.3.1.5 Spatiality

This method is most applicable to dairy, beef, poultry and pig farms where stocking rates result in the total amount of N in excreta exceeding 170 kg/ha N (the livestock manure N loading limit allowed under the Nitrate Vulnerable Zone Action Programme).

3.3.1.6 Displacement

Crop available nutrient supply from manures on the importing farm will reduce the need for manufactured fertiliser applications to meet optimum crop demand

3.3.1.7 Maintenance and longevity

Use of livestock manures and other organic materials will need investment in storage and spreading equipment.

Long-term agreements between importing and exporting farms will be required. The nutrients supplied by the manure on the importing farms should be included in nutrient management plans.

3.3.1.8 Climate adaption or mitigation

None

3.3.1.9 Climate factors/constraints

Wet soil conditions will limit the opportunity to apply manures without causing soil compaction or increasing the risk of nutrient losses in drainage or surface waters. Sufficient storage capacity and appropriate application equipment will be required to ensure that applications can be applied when soil and crop conditions are suitable (Defra project WQ0118, Chambers et al, 2000).

3.3.1.10 Benefits and trade-offs to Farmer/land manager

The need for manufactured fertiliser applications to meet optimum crop demand will be reduced on the importing farm. There will be costs associated with manure transport and applications. There may be opportunities to establish ‘muck for straw’ deals where the importing farm supplies straw to the exporting farm in return for the manure. Soil organic matter levels and the associated improvements in soil function (e.g. water holding capacity, soil structural stability, increased biological activity etc.) are likely to increase where the importing farm has no history of organic manure applications

3.3.1.11 Uptake

Uptake is likely to be restricted to arable farms in close proximity (e.g. within 5-20 km). to the exporting farm.

3.3.1.12 Other Notes

None

3.4 SLURRY STORAGE AND FARMYARD INFRASTRUCTURE

3.4.1 ECAR-004; ECPW-112; ECPW-185; ECPW-219

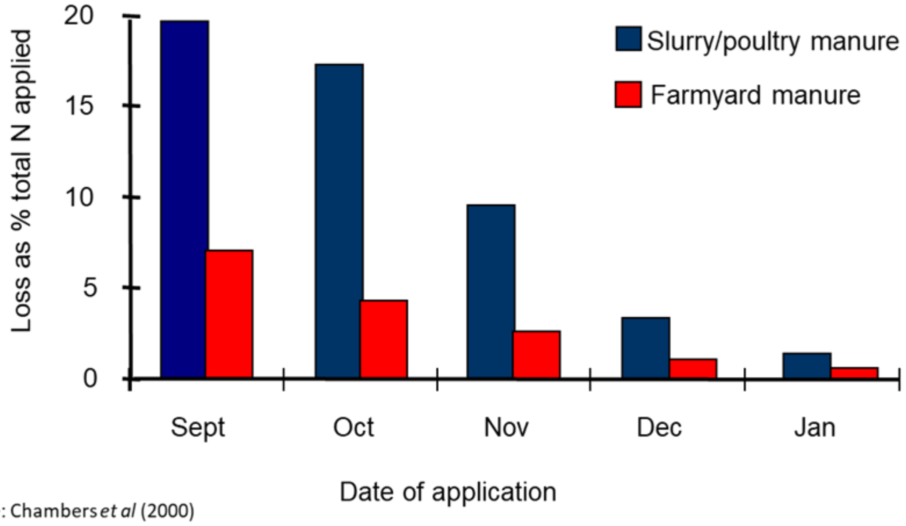
ECAR-004	Increase the capacity of farm slurry and manure stores to improve timing of slurry applications
ECPW-112	Separate clean water from dirty water and slurry (e.g. roofing over livestock yards, manure, slurry and silage stores, rainwater goods including gutters and downpipes,

	concrete yard renewal, sleeping policemen, cross drains and underground drainage, yard)
ECPW-185	Install/ maintain water drainage and storage equipment structures
ECPW-219	Ensure stores are resilient to a changing climate (e.g. not at risk of flooding or impacted by extreme temperature)

3.4.1.1 Causality

The collection and storage of slurry and solid manure increases the opportunities when manures can be spread at times when the risk of water pollution are low. Minimising the amount of water that enters slurry stores will reduce slurry volumes produced. In particular, there will be fewer occasions when a lack of storage capacity forces slurry application to occur when soils are wet and there is a high-risk of surface runoff or drain flow losses to water i.e. when soils are 'wet'. If a farm has little or no storage capacity for slurry, and/ or large volumes of water from roofs and concrete yards enter the store, it is inevitable that applications will be made at times when there is a high risk of water pollution.

Autumn applications of manures usually pose the greatest risk of nitrate leaching losses on all soil types as crop up take in the period after application and the start of overwinter is typically not enough to match the available N supplied (Chambers et al., 2000; Figure 4).



Source: Chambers *et al* (2000)

Figure 4. Nitrate leaching losses following contrasting manure application timings to winter cereals on free draining soils.

On drained soils, slurry applications to soils that have a soil moisture deficit of less than 20mm pose a significant risk of phosphorus and ammonium-N contamination of drainage water, as a result of rapid transfer of water from the soil surface to drains following rainfall (Figure 5, Defra project WQ0118). Increasing slurry storage capacity and minimising the volume of slurry produced will help ensure adequate facilities are available to optimise slurry application timings that minimise nitrate leaching and phosphorus, ammonium and microbial losses in surface runoff.

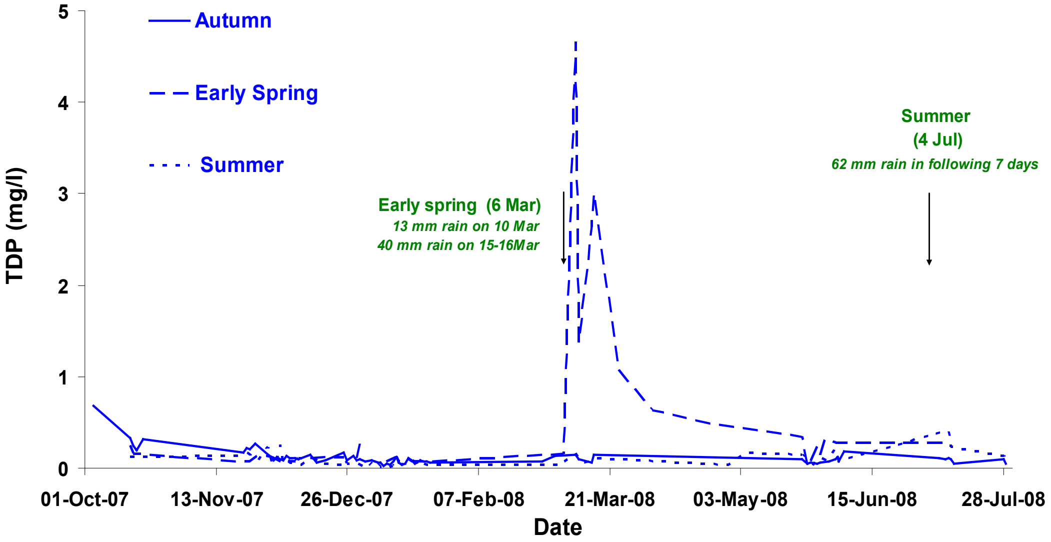


Figure 5. Total Dissolved Phosphorus (TDP) concentrations in drainage water following contrasting cattle slurry applications to drained clay soils under grassland (Defra project WQ0118).

3.4.1.2 Benefits and trade-offs

Reductions in nitrate losses to water following application will increase nitrogen use efficiency of the manures and reduce the need for manufactured fertiliser N applications to meet optimal crop demand. Ensuring that manure applications are made when soil conditions are suitable to withstand the weight of application machinery will reduce the risk of soil compaction.

[TOCB Report-3-2 GHG **ECAR-004**] Benefits of increased capacity for slurry and manure to improve timing of application include the reduction of loss of methane and ammonia into the air, reduction of Nitrous Oxide under cold conditions and the retention of additional nitrogen within manures which increases the value of slurry. Trade-offs centre around the cost of storage, and the long-term nature of payback. Overall, this strategy has the potential to result in much more efficient nutrient management with benefit for air and water quality.

3.4.1.3 Magnitude

The magnitude of nitrate leaching losses following autumn slurry applications will vary according to over winter rainfall after application, soil type and crop type. On free draining sandy soils with moderate rainfall, changing slurry application timings to winter cereals from autumn to spring are likely to reduce nitrate leaching losses by an equivalent of 20% of total N applied and by 10-15% on clay and medium soils. Nitrate leaching losses following slurry applications to oilseed rape and grassland will usually be lower (less than 10% of total N applied) reflecting crop N uptake in the period between application and the start of winter drainage.

3.4.1.4 Timescale:

Changing slurry application timings that increase the fertiliser replacement values of livestock manure applications will have an immediate effect on reducing the effects of water pollution.

3.4.1.5 Spatiality

This action will be most suitable on intensive dairy, beef and pig farms where manures are handled as slurry and in areas of high rainfall.

3.4.1.6 Displacement

Not assessed

3.4.1.7 Maintenance and longevity

Above ground slurry stores typically have an operating life of 20-25 years. Slurry is very corrosive so any damage to protective covering of steel plates will require maintenance. Abrasion of internal surfaces during emptying needs to be minimised in order to reduce the risk of damage. Regular inspections should be carried out to identify maintenance requirements, such as replacing bolts and renewal of sealant between panels. Earth banked lagoons lined with plastic sheeting are at risk of damage during emptying and plastic can deteriorate following exposure to sunlight. Special safety precautions should be observed, particularly against the presence of toxic gases when working in confined spaces and stores should be fenced off to minimise risks to the public. Roofing yards and ensuring clean water is separated from slurry stores will reduce slurry storage requirements

3.4.1.8 Climate adaption or mitigation

The increased frequency of periods of intense rainfall predicted as a result of climate change will increase the need for greater slurry storage capacity and to manage roof and yard water on farms.

3.4.1.9 Climate factors / constraints

The need for increased slurry storage is likely to be greatest in high rainfall areas. This reflects the greater likelihood of soil and weather conditions limiting opportunities for slurry to be applied when there is a low risk of water pollution.

3.4.1.10 Benefits and trade-offs to Farmer/land manager

Increasing slurry storage capacity should lead to better utilisation of slurry nutrients by allowing applications to be made when crops are actively growing. Increasing crop available nutrient supply from slurry applications will reduce the need for manufactured fertiliser applications to meet optimum crop demand. Reducing slurry volumes as a result of the amount of ‘clean’ water entering slurry stores will reduce slurry spreading costs.

3.4.1.11 Uptake

The cost of increasing slurry storage can be a barrier to uptake with the costs varying according to store type and slurry production. Construction costs are typically £50/m^3 for above ground steel and concrete stores and £40/m^3 for earth banked lagoons (NIX, 2020). Estimates of the capital costs for increasing slurry storage capacity from 3 months to 6 months for a dairy farm with 300 cows have been estimated at £115,000 (Defra project WQ0932).

3.4.1.12 Other notes

None

3.5 PREVENTING LIVESTOCK ACCESS TO WATERCOURSES

3.5.1 ECPW-170; ECPW-099; ECPW-103; ECCA-030

ECPW-170	Fence off rivers, streams, lakes and ponds from livestock to prevent bankside erosion, reduce nutrient input and faecal contamination, and prevent poaching
ECPW-099	Provide drinking water for livestock as an alternative to drinking from watercourses
ECPW-103	Construct bridges for livestock and machinery crossing watercourses

ECCA-030 Install/ enhance/ maintain infrastructure to cope with extreme events (culverts, bridges, access tracks etc.)

3.5.1.1 Causality

Livestock, particularly cattle, can cause severe damage to river and stream banks when attempting to gain access to drinking water. The vegetative cover is destroyed and the soil badly poached, leading to erosion of the bank and increased transport of soil particles and associated nutrients into watercourses. Similarly, machinery trafficking across rivers disturbs sediment, causes wave turbulence which can increase bank erosion increasing sediment concentrations. Livestock also add nutrients and Faecal Indicator Organisms (FIOs) by defecating and urinating directly into the water and vehicles can deposit sediment and chemicals. Fencing, providing alternative drinking water sources and constructing bridges to prevent bank access eliminates this source of pollution.

3.5.1.2 Benefits and trade-offs

Reducing sediment and nutrient inputs in rivers is likely to enhance freshwater biodiversity as well as riverbank and riverside habitats. The use of water troughs as an alternative to accessing water from rivers should be managed to reduce risks of soil compaction and soil damage by livestock in order to reduce the risks of nutrient runoff and increased nitrous oxide emissions.

[TO Report-3-6 Carbon **ECPW-220**] Soil compaction and damage through poaching (the process of removing surface vegetation cover by livestock trampling) is a common issue in British pasture. Analysis of survey squares as part of the Wales-wide Environment Rural Affairs Monitoring and Modelling Programme (ERAMMP) demonstrates that several types of poaching features are visible from aerial and satellite imagery including (Robinson et al., 2021; Tye & Robinson, 2020):

- Poaching around feeding areas
- Poaching where animals congregate for shelter or socialising (e.g. behind hedges or walls)
- Poaching in fields, particularly around farmyard access (e.g. where animals are congregated prior or after milking or for animal maintenance)
- General field poaching, trampling by animals

Additionally, gateway damage (where vehicles or livestock approach the point of egress) and exacerbation of terracettes (hillslope ridges formed by repeated wetting and drying cycles causing soil to move downslope) make the issue of moving livestock to avoid poaching a particular challenge (Tye & Robinson, 2020). However, the impact of this issue for carbon sequestration and storage has not been quantified (Bilotta et al., 2007; Pulley et al., 2021). The fate of carbon that is lost from terrestrial to aquatic systems is also unclear. Particulate organic matter may be subsequently sequestered in other wetland, coastal or marine habitats, and soil nutrients could prompt an increase in productivity in some systems (Beaumont et al., 2014; Quinton et al., 2010). Where vegetation is allowed to recover, there could be an increase in above ground biomass.

3.5.1.3 Magnitude

Kay et al. (2018), suggested that grazing cattle spent disproportionately large amounts of time in watercourses and riparian zones along unfenced rivers, especially during the summer months when water flows are typically low and bathing waters are particularly vulnerable to FIO contamination. A study carried out on the river Tamar measured FIO concentrations before and after fencing a 271m long stretch of the river. *E. coli* and Intestinal Enterococci loads in high flow stream events after fencing were 0.842 and 2.206 $\log_{10}$, lower, respectively than when the livestock had access to the river. Muirhead (2019) reported results from a meta-analysis of 18 papers which showed that the effectives of stream fencing at reducing FIO concentrations of stream waters covered a large range, from zero to 96%, with a median value of 62%.

At a catchment scale, reductions in N and P losses to water are likely to be small as the main sources are from leaching and surface runoff from agricultural land.

3.5.1.4 Timescale:

Improvements In water quality are likely occur with 0-6 months of fence or bridge installation.

3.5.1.5 Spatiality

This method is applicable to all farms where there are stream crossings without bridges. It is especially applicable on livestock farms and dairy farms in particular where cows are moved between the fields and milking parlour on multiple occasions during the day.

3.5.1.6 Displacement

None

3.5.1.7 Maintenance and longevity

These actions are usually low maintenance with farm fences expected to last at least 20 years.

3.5.1.8 Climate adaption or mitigation

None. General improvement of farm infrastructure to cope with increased rainfall?

3.5.1.9 Climate factors/constraints

None.

3.5.1.10 Benefits and trade-offs to Farmer/land manager

There will be increased costs associated with fence installation, bridge construction and the provision of alternative sources of drinking water. Farm fencing typically costs between £5 -£10/ metre (Nix, 2020). Bridge construction costs will vary depending on the scale of construction required and whether farm labour and equipment can be used. Improving access to pasture by building bridges has the potential to reduce feed and labour costs. Similarly, better access for machinery is likely to reduce travel times and distances on farm thereby saving energy and labour costs. Mains water, private water supplies or installation of river water abstraction systems are alternative sources of drinking water.

3.5.1.11 Uptake

Fencing streams is less applicable to upland livestock farms with extensive areas of rough grazing and considerable lengths of unfenced river and stream banks. Reference alternatives to fencing such as electrical stimulators?

3.5.1.12 Other notes

None

3.6 COVER CROPPING AND SOIL PROTECTION

3.6.1 ECPW-002; ECPW-095; ECPW-295; EHAZ-004; ETPW-229; ECCM-001; ECPW-181

ECPW-002	Minimise bare soil to reduce soil loss (e.g. cover crops, crop residues, trees coppice etc.)
ECPW-095	Maintain soil cover (e.g. grass, crop or geotextile) to reduce soil erosion and loss around field structures, such as poly-tunnels, plastic sheeting /cloches or irrigation equipment used for horticultural crops
ECPW-295	Maintain soil cover (e.g. grass, crop or geotextile) to reduce soil erosion and loss around livestock shelters/feeders/troughs (e.g. for outdoor pigs)
EHAZ-004	Use under and over sowing
ETPW-229	Enhanced overwinter stubble
ECCM-001	Diversify arable rotations (including cover and catch crops, over and under sowing)
ECPW-181	Conversion to a more extensive system including reversion from high-risk forage to grass and whole crop and reduced inputs

3.6.1.1 Causality

Nitrate leaching losses are typically highest from land left bare during the autumn and winter period as mineral nitrogen remaining in the soil after harvest is not taken up by growing crops (Figure 6). Also, land left bare over winter increases the risk of soil erosion which leads to sediment and particulate P loss in surface runoff (Figure 7). To be effective at reducing NO_3 leaching, cover crops should take up N before the onset of winter drainage, but thereafter the date of destruction is less critical. To be effective at reducing particulate P and sediment losses the cover does not have to be alive (i.e. straw and crop residues can be effective), but the soil must be protected throughout the period when surface runoff can occur. Physical barriers, such as geotextiles, can be effective at protecting soils from erosion and limit sediment and P losses to water from high-risk areas, such as areas around polytunnels, livestock shelters and feeders.

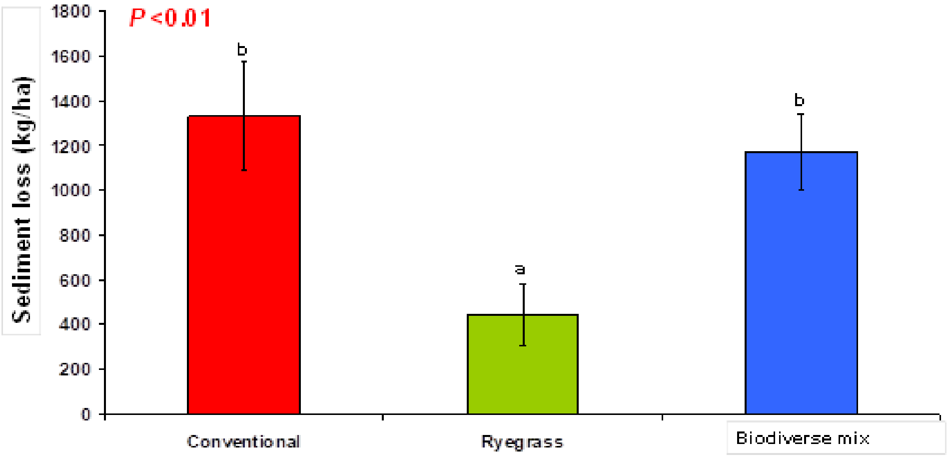


Figure 6. Impact of contrasting cover crops on sediment loss following maize cropping (conventional is the control i.e. maze stubble; Defra project WQ0140)

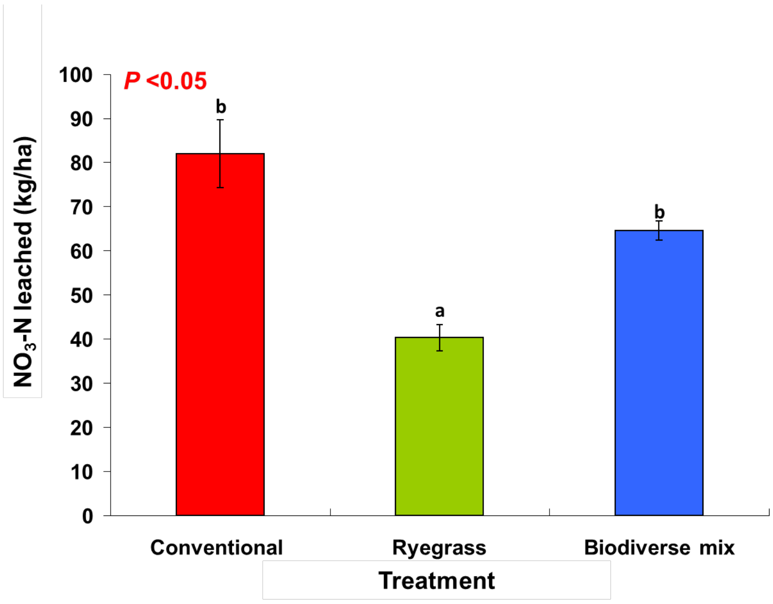


Figure 7. Impact of contrasting cover crops on nitrate leaching loss following maize cropping (conventional is the control i.e. maze stubble; Defra project WQ0140)

3.6.1.2 Benefits and trade-offs

Reducing sediment and nutrient inputs in rivers is likely to enhance freshwater biodiversity as well as riverbank and riverside habitats. A proportion of the nitrogen accumulated in the cover crop will become available for crop uptake by the following cash crop, reducing the need for manufactured fertiliser applications to meet optimal crop demand. The cover crop residues will also provide a source of organic matter which will help maintain and improve soil function especially in soils with sub-optimal soil organic matter content.

[TOCB Report-3-5D Systems **ECPW-002**] Minimise bare soil to reduce soil loss: This has not been reviewed for biodiversity as it is too general: the various options will have a range of negative and positive effects for different species, which will be variable across action-taxon combinations.

[TOCB Report-3-5D Systems **ECPW-181**] Conversion to a more extensive system: This is a general nutrient management action, from which we expect an overall reduction in nutrient inputs, with various positive effects on biodiversity. At the whole-farm level, these could be quite significant. However, effects will depend on the context of baseline nutrient levels.

3.6.1.3 Magnitude

Reductions in nitrate leaching achieved by cover cops or weedy stubble will depend on factors including the effectiveness of cover crop establishment, over winter rainfall and the residual soil mineral nitrogen content of the soil following the previous cash crop. Generally, well established cover crops (i.e. drilled before the end of August) will typically reduce nitrate leaching losses, phosphorus and sediment losses to surface waters by more than 50% compared with bare ground. Where land is taken out of arable production by planting trees or short rotation coppice, it is likely that nitrate leaching, sediment and P losses will reduce to background levels. Erosion control provided by geotextiles is likely to reduce sediment and P losses in surface runoff by more than 50% compared with bare ground.

3.6.1.4 Timescale

Well established cover crops will reduce nitrate leaching, sediment and P losses in surface runoff compared with leaving soil bare over winter in the winter season immediately after establishment.

Similarly, the use of geotextile materials on vulnerable areas will result in reductions in erosion and P loss immediately after installation. Taking land out of arable production by planting trees or short rotation coppice is likely to return nitrate leaching and P and sediment losses in surface water to background levels within 5 years of establishment (Williams et al., 1995).

3.6.1.5 Spatiality

Cover crop establishment is applicable on all farms where spring crops are grown and land would normally be left bare over winter after harvest of the previous crop. The use of geotextile materials is most suited to 'hot spots' for erosion, such as where soil has been damaged around polytunnels, livestock feeders, exposed earth river banks etc.

3.6.1.6 Displacement

None

3.6.1.7 Maintenance and longevity

Cover cropping takes place annually. Tree establishment is likely to require maintenance as the stand matures e.g. ensuring stem guards are in place following planting, and thinning and coppicing as the trees grow. Geotextiles will require replacing every 2-3 years depending on the level of damage caused by machinery and livestock traffic etc.

3.6.1.8 Climate adaption or mitigation

None

3.6.1.9 Climate factors/constraints

Cover crop establishment is controlled by soil conditions at the time of and in the weeks after drilling. If soils are too dry, then seed germination may be delayed resulting in poor establishment. Weather and soil conditions are also important factors controlling the effectiveness of cover crop destruction prior to the establishment of the following crop.

3.6.1.10 Benefits and trade-offs to Farmer/land manager

For cover crop establishment there will be additional costs associated with seed, establishment and destruction of the cover crop. Although costs may be reduced by using home saved seed or by allowing the establishment of weedy stubble over winter. Additional field operations to destroy cover crops may compromise establishment of the following cash crop leading to reduce yields. Where spring crops follow well established cover crops it may be possible to reduce manufactured nitrogen fertiliser applications as some of the nitrogen taken up by the cover crop over winter will be mineralised during the growing season and available for use for the cash crop. The use of geotextiles which are not bio-degradable may increase the risk of soil and water pollution unless they are managed correctly

3.6.1.11 Barriers to Uptake

Cover crop establishment is most applicable to tillage land, particularly light soils, which are most suited to spring cropping. There will be additional costs to the farm business, including seed and cultivations and herbicide costs associated with cover crop establishment and destruction.

3.6.1.12 Other notes

None

3.7 SHEEP DIP MANAGEMENT

3.7.1 ECPW-216; ECPW-257; ECPW-260

ECPW-216	Follow the *'Sheep dip: Groundwater Protection Code'*
ECPW-257	Relocate sheep veterinary treatment areas and pens to appropriate locations
ECPW-260	Use sheep dip drainage aprons and sumps

3.7.1.1 Causality

Many sheep flocks in the UK are treated with insecticides to control ectoparasites and fly strike, which has major welfare and economic impacts for the sector (Cross et al. 2010). Treatment can occur in the form of plunge dipping, where animals are submerged in a dip containing either an organophosphate (OP) compound (e.g. diazinon) or a synthetic pyrethroid (SP) (e.g. cypermethrin), or through the application of a ‘pour-on’ containing an SP. Both OPs and SPs are hazardous substances, and whilst they have been shown to have some impacts on soil biology (Boucard et al. 2008), it is their impact on water pollution that is of greatest concern (Virtue and Clayton, 1997). Implementing the three measures listed above reduces the risks of run-off and leaching into above- and below-ground water bodies.

Specifically, following the *‘Sheep dip: Groundwater Protection Code’* (**ECPW-216**) will ensure that the personnel who purchase and use the chemicals have achieved a certification of competency and have obtained the necessary permits, and that treatment occurs in appropriate weather. Following the Code would mean that the facilities are: made of appropriate materials (e.g. concrete or UV-resistant plastic), are suitably sited (e.g. avoiding floodplains and being of at least 10m from a watercourse) and maintained in an intact condition (e.g. leaks fixed), are designed to contain splashes and run-off post-dipping, and that the holding area post-dipping is sufficiently large to contain the sheep until they have dried and excess dip has dripped back into the bath. There are also detailed guidelines on the storage and disposal of unused chemicals and the solution within the dip bath (e.g. the chemical diluted with water). These revolve around suitable storage areas (e.g. bunded, impermeable), the destruction of containers, and how to mix used dip solution with slurry before spreading on designated fields in appropriate conditions. There is also a requirement to keep records of the use and disposal of sheep dip. The code is relevant to farms with their own dipping facilities, and the increasing number who use contract dipping services with mobile units.

Relocating sheep veterinary treatment areas and pens to appropriate locations (**ECPW-257**) pertains to the use of ‘pour-on’ insecticides, as well as areas where dipping is practised. Whilst the volume of liquid applied via ‘pour-on’ treatment (<100 ml/sheep) is much smaller than when sheep are submerged in a dipping tank, only small volumes of SPs entering water bodies is sufficient to cause a pollution incidence. This may occur when sheep enter streams and rivers to drink post-treatment, for instance. Pens that are sited near such water bodies could be relocated, with sufficiently large holding areas to retain livestock post-treatment, until they have dried out. As well as suitable bases and design, such areas may need piping of water from a water source and a non-returnable valve, so that livestock do not enter watercourses following treatment. The same principles apply to areas where cattle are to be treated with insecticides via ‘pour-on’ methods, though the risk of SPs entering waterbodies following cattle treatment should be much lower.

Using sheep dip aprons and sumps (**ECPW-260**) is specifically targeted at farms that employ mobile dipping services. Such farms may not have the infrastructure in place to contain the excess solution, and/or their own infrastructure does not comply with the requirements of ‘*The Groundwater Protection Code’*. Relocating sheep dipping areas and pens can help reduce risk of diffuse water pollution. This measure aims to provide an apron designed to redirect drainage water from the pen area back to the dip bath, using suitable material (e.g. impermeable concrete), and to incorporate a sump to catch debris, such as wool and faeces, and prevent it from re-entering the dipping tank; designed and sited in a way to comply with '*The Groundwater Protection Code'*.

Collectively, implementing these three measures should considerably reduce the risk of polluting waterbodies from insecticide treatment of livestock.

3.7.1.2 Co-Benefits and trade-offs

Done well, plunge dipping is known to be effective in the treatment and prevention of ectoparasites and fly strike for sheep (SRUC, 2011). However, without grant funding, the cost of the infrastructure required for plunge dipping may be prohibitive to farmers, with implications for sheep welfare.

There should be no trade-offs as these measures would be a way to facilitate what is already mandatory.

[TOCB Report-3-5B Grassland **ECPW-257**] Relocate sheep veterinary treatment areas and pens assumes not on, or affecting semi-natural habitats, then conserving biodiversity.

3.7.1.3 Magnitude

Tightening of the regulations around the purchase, use and disposal of sheep dip, together with a substantial increase in costs, means that there are likely to be far fewer farms operating these facilities themselves. Many will have moved to use contract dippers (who, in theory, could justify the investment in better facilities and management), or switched to use 'pour-on' treatment of injectable drugs (e.g. doramectin), the latter of which avoids almost all the associated risks to water quality posed by OPs and SPs. Nevertheless, the toxic nature of OPs and SPs means that small leakages can have major impacts on water quality, and there are still likely to be many sites in use, with the potential for more in areas where sheep numbers are increasing.

3.7.1.4 Timescale

Given that farmers that use sheep dip must already comply with the stipulations of the '*Sheep Dip: Groundwater Protection Code'*, these measures should not lead to a sudden improvement in water quality. Nevertheless, the measures could still offer an opportunity for farmers to improve their facilities and thereby reduce the risk of water pollution in the short term.

3.7.1.5 Spatiality

These measures are most relevant to sheep-dominated areas such as the uplands. However, given the increasing (re)integration of sheep into arable-dominated areas, they have relevance across many regions – especially given that such farms are unlikely to have facilities that meet the necessary standards.

3.7.1.6 Displacement

None.

3.7.1.7 Maintenance and longevity

The '*Sheep Dip: Groundwater Protection Code*' stipulates that farms that have invested in the infrastructure to use sheep dips need to check the site and bath, and any cracks or breakages that would lead to leakage will need to be repaired prior to use. With the appropriate maintenance, the infrastructure should remain operational for many years.

3.7.1.8 Climate adaption or mitigation

None.

3.7.1.9 Climate factors/constraints

None.

3.7.1.10 Benefits and trade-offs to Farmer/land manager

Incidences of sheep challenged with ectoparasites are in the increase, and plunge dipping is still regarded as the optimal way for their control, whilst also offering protection against fly strike (SRUC, 2011). Ensuring suitable facilities are in place to allow plunge dipping to continue could reduce the economic burden on the sheep sector, whilst the welfare benefits to sheep would offer peace of mind to their owners.

3.7.1.11 Uptake

The *'Sheep Dip: Groundwater Protection Code'* and the associated permits and licenses are already mandatory, though the degree of (non)compliance cannot be ascertained. Grant funding has been available through the Countryside Stewardship Scheme (RP22) for the purchase of sheep dip drainage aprons and sumps, though it is unknown how many have capitalised on this. Given the reported increase in integration of sheep grazing into arable rotations, then there is still likely to be uptake in some regions.

It has long been reported that there is some resistance to SPs by some sheep (and cattle) ectoparasites (Johnson et al. 1992; Mckiernan et al. 2021), therefore the demand for plunge dipping with OPs and associated infrastructure is likely to remain.

3.7.1.12 Other notes

None

3.8 BUFFER STRIPS

3.8.1 ECPW-042; ECPW-291; ETPW-038; ECPW-157EM; ECPW-157C

ECPW-042	Create/ enhance/ manage riparian buffer strips
ECPW-291	Create/enhance/manage riparian habitats
ETPW-038	Create/ manage/ enhance buffer strips
ECPW-157EM	Enhance/ manage/buffer strips (including trees) around boreholes
ECPW-157C	Create buffer strips (including trees) around boreholes

Within this review, we define buffer strips as permanent or semi-permanent vegetation strips that replace agricultural land (grassland and arable), and are adjacent to water features, with the aim of providing a buffer for nutrient, sediment and pesticide loss from the agricultural activity to the watercourse. The vegetation can range from ungrazed grass, bushes, hedgerows and woodland.

3.8.1.1 Causality

Actions **ECPW042**, **ECPW-291** and **ETPW-038** are potentially most effective on sloping tillage land, in fields that are vulnerable to soil erosion (e.g. land used for outdoor pigs, and late harvested crops) (Feld et al, 2018). The actions may reduce water pollution in two ways. They distance agricultural activity from watercourses, and therefore reduce direct pollution from fertiliser, organic manure additions and pesticides, and can restrict direct livestock access to watercourses. They can potentially intercept surface runoff from agricultural land before it reaches the watercourse, therefore acting as a sediment trap and filter for nutrients. The buffer vegetation can also take up P and N through their roots from soil water

(**Muscutt** et al. 1993). Buffer strips are most effective if they are free-draining and have a good surface porosity to intercept surface runoff.

The establishment of permanent riparian vegetation cover also has the potential to reduce peak flows thereby reducing the risk of flooding but also limit flows during drought. Conversely, tall vegetation will provide shading that will reduce water temperatures and evaporation (Bowler et al, 2012).

Trees and large bushes close to watercourses can slow river flow and hold back water during floods due to increased hydraulic roughness. The reduction in flood peaks across a catchment can also reduce flood risk in the lower catchment (Burgess-Gamble et al. 2018). The slowing of river flow velocities will also reduce channel erosion during flooding and increase the rate of sedimentation on floodplains.

Actions **ECPW-157EM** and **ECPW-157C** are limited to distancing agricultural activity from areas around boreholes. They will be effective at reducing the risk of nitrate leaching and pesticide losses to aquifers by taking land out of agricultural production which will stop cultivations and applications of manufactured fertilisers, organic materials and pesticides in the area around the borehole.

3.8.1.2 Co-benefits and trade offs

Reductions in sediment, P and pesticide inputs to water are likely to improve the aquatic ecology and biodiversity. In addition, tall riparian vegetation can reduce summer water temperatures and solar radiation, which could reduce fish stress, increase invertebrate biodiversity and biomass (Thomas et al, 2016), algal growth rates (McCall et al. 2017) and dominance of cyanobacteria (blue-green algae) (Paerl and Huisman 2008). Buffer strips also have the potential to enhance terrestrial biodiversity by providing a refuge for wildlife encouraging the growth of non-crop plant species and providing a connected network of natural areas. Establishing permanent ground cover on previously cultivated land will increase carbon storage in the area covered by the buffer strip.

3.8.1.3 Magnitude

The effectiveness of the action is likely to reflect the size of the buffer strip and where they are free-draining and have a good surface porosity to intercept surface runoff. Land management schemes offer options for buffer strips between 2 and 6 m in width, and 10 m around in-field ponds. Leaving a 3 to 6 m buffer between pesticide applications and watercourses has been shown to result in up to 95% reductions in pesticide input to the stream (Borin et al. 2004, de Snoo and de Wit 1998).

Previous studies have shown that buffer strips can be very effective at reducing sediment loads, with sediment trapping rates of 84% reported whilst strips of >15m were required to reduce P loads (Abu-Zreig et al. 2004). However, other studies did not detect any impact on stream N and P concentrations following the establishment of vegetated buffer strips (Bullock et al. 2021, Collins et al. 2013). This is unsurprising, as much agricultural land in the UK is under-drained and therefore the water and associated nutrients, pollutants and sediments are very likely to bypass most buffer strips.

Establishing buffers around boreholes would be expected to reduce nitrate and pesticide losses from the area taken out of agricultural production to background levels. The impact on the losses to the aquifer will depend on the proportion of the catchment area taken out of production.

3.8.1.4 Timescale

The actions will be effective once the cover has established which is likely to take between 6-12 months for surface cover and several years where hedges and trees are planted.

3.8.1.5 Spatiality

Riparian buffer strips can be applied across all farms where there are watercourses.

3.8.1.6 Displacement

In tillage systems, there will be some reductions in crop yields with the magnitude dependant on the area taken out of production.

3.8.1.7 Maintenance and longevity

Once established buffer strips generally require little maintenance, however there can be issues with weed control. It is important to prevent vehicle trafficking to minimise the risks of soil compaction which can reduce their effectiveness in controlling nutrient and sediment losses to surface water systems. The action needs to be maintained indefinitely for the benefits to persist.

3.8.1.8 Climate adaption or mitigation

Taking cultivated land out of production and maintaining permanent vegetative cover will increase the potential for soil carbon accumulation on the area of land covered by the buffer strip. Wooded buffer strips have the potential to provide light shading, which can reduce water temperatures, supress excessive algal growth (Hutchins et al, 2010), improve fish spawning (Jonsson and Jonsson, 2009) and provide some catchment resilience to climate change (Bowler et al. 2012). Wooded buffer strips can also decrease flood water velocity along the river channel, which could potentially reduce peak flows downstream (Climate_Adapt https://environmentalevidence.org/project/what-are-the-effects-of-wooded-riparian-zones-on-stream-temperature-systematic-review/).

3.8.1.9 Climate factors/constraints

None.

3.8.1.10 Benefits and trade-offs to Farmer/land manager

Taking land out of production will reduce crop yields however taking low production potential land out of production and including it in a land management scheme may compensate for any loss in income.

3.8.1.11 Barriers to Uptake

Buffer strip establishment is most suited to areas of low to moderate production potential.

3.8.1.12 Other notes

None

3.9 HABITAT CREATION – WETLAND FEATURES

3.9.1 EBHE-164C; EBHE-164EM; ECCA-013C; ECCA-013EM

EBHE-164C	Create wetland habitats
EBHE-164EM	Enhance/ manage wetland habitats
ECCA-013C	Create artificial wetlands
ECCA-013EM	Enhance/ maintain artificial wetlands

3.9.1.1 Causality

Wetlands created simultaneously promote nutrient retention and biodiversity conservation, which eventually lead to a strong benefit to improve freshwater ecological quality. In wetland ecosystems, the largest part of biologically available organic matter is provided by aquatic vegetation. Ibekwe et al. (2007) reported that experimental constructed wetland cells with 50% plant cover had as high as 96·3% nitrate removal, whereas the nitrate removal in the 100% plant cover cells was about 11·4%. A high oxygen level is a key factor in maximising the degradation of organic matter in wetlands, and the microbial community should serve as an excellent indicator to monitor the biological and chemical responses of the wetland to variable oxygen levels (Godshalk and Wetzel, 1978; Ibekwe et al., 2007).

3.9.1.2 Co-Benefits and Trade-offs

Creating wetland landscape may alter previous soil/sediment properties, hydrology and water quality conditions. During the wetland restoration process, various environmental parameters, such as nutrient level, pH, oxygen level, and salinity may be altered, and these changes will be reflected by various biological communities. Wetland restoration efforts could benefit from increased denitrification mediated by denitrifying bacteria in natural wetlands. However, constructed wetlands may have lower microbial diversity and functions in comparison with natural wetlands (Hartman et al., 2008).

3.9.1.3 Magnitude

Catchment-scale wetland creation for simultaneous retention and diversity purposes benefits the biodiversity of agricultural landscapes, particularly if the density of aquatic habitats is increased by at least 30% (Thiere et al., 2009).

3.9.1.4 Timescale

>10 years
Card and Quideau (2010) reported a similar microbial community composition and biomass between the restored sites (7–11 years) and the reference sites of the Prairie Pothole Region of Canada, indicating the success of restoration efforts.

Bernhard et al. (2012) reported no difference in bacterial community composition in restored marshes after 30 years but found significant differences in community variability of the restored marshes compared to undisturbed marshes, suggesting a potential long-term effect.

Additionally, significantly higher abundances of nitrogen cycle microbes were found in subsurface salt marsh sediments 30 years after restoration, indicating that full recovery had not been achieved (Bernhard et al., 2015).

3.9.1.5 Spatial Issues

Wetland density promoted alpha (local, species richness) and beta (regional spatial heterogeneity, community differences) biodiversity of aquatic macroinvertebrates, while the beta diversity remained high which represent a high spatial heterogeneity, independent of wetland density (Thiere et al., 2009; Fuentes-Rodriguez et al., 2013; Reyne et al., 2020).

3.9.1.6 Displacement

Creating wetlands on agricultural land will take land out of production

3.9.1.7 Maintenance and Longevity

No assessment.

3.9.1.8 Climate Adaptation or Mitigation

The influence of global warming will impact the future of wetlands. Generally, wetlands are considered the largest nonanthropogenic source of atmospheric methane, but they can also be a sink by changing the level of the water table (Hanson and Hanson,1996). Methane is slowly released from bogs as the permafrost melts, caused by global warming.

Estuarine wetlands have a capability to protect the coastline from erosion and flooding, but with increasing global temperatures, sea level increases, more wetlands will be under the sea (up to 22% of the world's coastal wetlands by the 2080s) (Nicholls et al., 1999).

3.9.1.9 Climate Factors / Constraints

None

3.9.1.10 Benefits and Trade-offs to Farmer/Land-manager

Taking land out of production may reduce farm income by reducing productivity. It is likely that wetlands will be established on land likely to flood which would be less suitable for agricultural production than well drained land.

3.9.1.11 Uptake

No assessment.

3.9.1.12 Other Notes

With the control of redox potential, the retention time of water, and the selection of soil and vegetation, we might create a desired constructed wetland, which has elevated performance in nutrient and pollutant removal.

Wetland condition and restoration cannot be met effectively by a single physical, chemical or biological parameter but a combination of multiple attributes is effective for robust wetland assessment and management. Establishing whether a wetland is recovered is very complex and cannot be determined from a single metric, and in many cases, some aspects may show strong recovery, while others are much less resilient (Urakawa & Bernhard, 2017).

3.10 RESTORATION, MANAGEMENT AND ENHANCEMENT– RIVER RESTORATION

3.10.1 ECCA-006; ECPW-066

ECCA-006	Re-naturalise river catchments by, for example, reconnecting rivers with their floodplain, restoring and realigning rivers, and restoring associated floodplain habitats
ECPW-066	Reinstate river meanders

3.10.1.1 Causality

River re-naturalisation strategies provide a range of aquatic and riparian environments capable of supporting a high aquatic biodiversity and increase nitrate uptake, which enhance the resilience of riverine ecosystem to disturbance and self-purification capacity. This is highly beneficial for river ecological water quality improvement because high biodiversity is commonly associated with habitat heterogeneity (case-study examples in Addy et al (2016)). River bends and meanders are particularly complex morpho-dynamic elements of watercourses consistent with spatio-temporal scales of invertebrate mobility and life cycle. Furthermore, the presence of flow refugia, and hydraulic dead zones in meanders is essential to sustain species richness (Garcia et al., 2011).

3.10.1.2 Co-Benefits and Trade-offs

The pre-eminence of flood-control objectives implicit in traditional engineering practises of river restoration aims at mitigating nutrient pollution, diverse flow and morphology with riffles and pools. However, biotic substrates like dead wood or macrophytes were more abundant in the restored reaches. In addition, differences in hydrologic conditions and sediment characteristic back river persistence to extreme climate.

3.10.1.3 Magnitude

Jähnig et al. (2010) compared restoration effects using Shannon–Wiener Indices (SWIs) of morphology and benthic invertebrate communities by investigating 26 pairs of non-restored and restored sections of central and southern European rivers. Mean SWIs differed for both mesohabitats (1.1 non-restored, 1.7 restored) and microhabitats (1.0 non-restored, 1.3 restored), while SWIs for invertebrate communities were not significantly different (2.4 non-restored, 2.3 restored). They conclude that restoring habitat on a larger scale, using more comprehensive measures and tackling catchment-wide problems (e.g., water quality, source populations) are required for a recovery of the invertebrate community.

Another survey included 44 river restoration projects located in Germany, compared riverine community metrics and revealed significant positive differences for 5 richness metrics (number of taxa, genera, families, within pollution-sensitive invert taxa, such as Ephemeroptera, Plecoptera and Tricoptera (EPT-taxa) and EPTCBO-taxa (EPT taxa plus Coleoptera, Bivalvia and Odonata) and the two sensitivity/tolerance indices Biological monitoring working party (BMWP) and average score per taxon (ASPT) (Leps et al., 2016). The taxon richness increased significantly from 34 to 38.1 taxa, with the sensitive taxa being mainly responsible for these gains, which showing strong turnover.

In addition, a 100 m stretch was surveyed for submerged and emergent macrophytes confirmed that macrophyte communities benefited from river restoration by showing increased cover, abundance and diversity. The highest number of species (23) was found in the restored reach. These 23 species comprised a total of 10 different growth forms. The average number of taxa was 4.4 in the unrestored reaches and 9.1 in the restored reaches (Lorenz et al., 2011).

Studies of the River Cole (Oxfordshire) and Wensum have shown that plant and invertebrate biodiversity has rapidly improved due to river restoration projects, and fish numbers have also increased (Addy et al, 2016).

3.10.1.4 Timescale

Major restoration programmes including re-meandering and channel profiling can be initially destructive, but studies have shown that aquatic ecology can start to recover within a year or two of restoration, but usually needs more than 10 years for aquatic ecology to become fully established. Addy et al (2016) report that invertebrate communities can rapidly recover within only one (River Cole, Oxfordshire) or two years (Rottal Burn, Angus). Macrophyte recovery can also occur over a few years after restoration.

Lorenz et al. (2009) reported the effects of two river restoration projects on two German lowland rivers in rural area, diversity was high in both two and ten years restored reaches; overall abundance increased only in the river that was restored 10 years ago.

Eekhout et al. (2015) confirmed the improvement of the abiotic conditions determinative to stream ecology. They reported that within 2-years natural processes caused an increase of the habitat heterogeneity in a reconstructed lowland stream.

Biological recovery will depend on the scale of the intervention and its connectivity with wildlife refugia across the catchment, to provide populations of sensitive taxa to recolonise.

3.10.1.5 Spatial Issues

No assessment.

3.10.1.6 Displacement

No assessment. May alter field boundary and size.

3.10.1.7 Maintenance and Longevity

In channel bends, the cross-sectional shape transformed from trapezoidal to the typical asymmetrical shape was found in re-meandering rivers (Eekhout et al., 2015). This behaviour can be attributed to an autogenous response to the prevailing flow conditions. Due to the prevailing fine sediment characteristics, bed material is readily set in motion and is being transported during the entire year. Design procedures for reinstate river meanders in lowland rivers need to improve the conditions for stream organisms, they recommend prediction of morphological developments as part of the design procedures during lowland stream restoration.

3.10.1.8 Climate Adaptation or Mitigation

Recreating pool – riffle sequences to modified rivers and diverse hydrology can provide refuges for aquatic organisms during both floods and droughts. Restoration of riparian vegetation can provide shading and mitigate against increasing air temperatures. Ability to make space for water and capacity for extreme weather events.

3.10.1.9 Climate Factors / Constraints

No assessment. See above.

3.10.1.10 Benefits and Trade-offs to Farmer/Land-manager

No assessment. Reconnection with floodplain may limit agricultural use.

3.10.1.11 Uptake

No assessment.

3.10.1.12 Other Notes

None

3.11 RESTORATION, MANAGEMENT AND ENHANCEMENT– WATER LEVEL, DAM MAINTENANCE

3.11.1 ECCA-008; EBHE-097; EBHE-212

ECCA-008	Create/ enhance/ maintain high flow storage reservoir
EBHE-097	Enhance/ maintain designed or engineered water bodies
EBHE-212	Create/ maintain raised water level areas by appropriate installation and operation of water level control

3.11.1.1 Causality

Water level controls help maintain the continuum of river networks which can be important to minimise the loss of biodiversity (Doretto et al., 2020). Increasing the water level can improve sediments stabilisation but reduce the water column dynamics. The use of water level controls can increase flood protection during extreme flow events. However, diminished natural flows lead to negative impacts to biodiversity. For example, the changes of water level which result affect water temperature which is important signal for larvae and juvenile fish in the river network (Taylor et al., 2014; Maheu et al., 2016; Dattilo et al., 2021). Water levels and water level variation are an effective control of algal blooms in rivers (Bergey, 2010; Xia et al., 2020).

3.11.1.2 Co-Benefits and Trade-offs

No assessment.

3.11.1.3 Magnitude

No assessment.

3.11.1.4 Timescale

No assessment.

3.11.1.5 Spatial Issues

No assessment.

3.11.1.6 Displacement

No assessment.

3.11.1.7 Maintenance and Longevity

No assessment.

3.11.1.8 Climate Adaptation or Mitigation

No assessment.

3.11.1.9 Climate Factors / Constraints

No assessment.

3.11.1.10 Benefits and Trade-offs to Farmer/Land-manager

No assessment.

3.11.1.11 Uptake

No assessment.

3.11.1.12 Other Notes

With the control of redox potential, the retention time of water, and the selection of soil and vegetation, we might create a desired constructed wetland, which has elevated performance in nutrient and pollutant removal.

3.12 RESTORATION, MANAGEMENT AND ENHANCEMENT– BANK RESTORATION

3.12.1 ECPW-220; ECCA-020

ECPW-220	Use willow spiling
ECCA-020	Create/ enhance/ maintain small barriers in ditches

3.12.1.1 Causality

Willow spiling based method for bank erosion control is generally believed to increase the stability of riverbanks. Stabilising effects from the willow include reinforcement of soil by rooting systems and the reduction of soil moisture content through canopy interception and evapotranspiration. They enhanced stream habitat by providing a zone of shallow still water along banks, attractive for aquatic plants and macroinvertebrates (Anstead, 2012).

3.12.1.2 Co-Benefits and Trade-offs

A case study in the Ballinderry River in Northern Ireland reported that after a number of hard and soft engineering techniques, including willow spiling bank restoration, initial observations suggest that river substrates are cleaner (Horton et al., 2015). The restoration project provided the local community with a better understanding of the habitat requirement of wild mussels (i.e., *Margaritifera margaritifera*) and its conservation of the freshwater pearl mussel in the Ballinderry catchment.

[TOCB Report-3-6 Carbon **ECPW-220**] Use willow spiling: Expert opinion suggests the use of willow spilling will have a small, positive effect on carbon sequestration due to the stabilisation of riparian sediments and reduced erosion. In addition, continued growth and carbon sequestration by the willow may have a small contribution to carbon sequestration. This effect will likely be negligible at the national scale and compared to the potential impact of other initiatives. The use of willow spilling is also likely preferable to other materials which are associated with a positive carbon emissions footprint, or which use non-living wood biomass which will decompose at a faster rate.

3.12.1.3 Magnitude

No assessment.

3.12.1.4 Timescale

Around 1 year. Long willow canes are woven around vertically driven willow poles and because structures are living, resistance to erosion increases over time.

3.12.1.5 Spatial Issues

No assessment.

3.12.1.6 Displacement

No assessment.

3.12.1.7 Maintenance and Longevity

Maintenance of the project depends on the project objectives, but it always beneficial to coppice the revetment at least once every three years (McCulloch, 2000). A small stream would not benefit from a vigorously growing variety of willow which would need frequent cutting back (Jarvis & Richard, 2008).
The total lifespan of willows is about 40 years under natural conditions, but in the absence of competition from other woody plants and if bushes are pruned on a regular basis, lifespan may exceed 100 years (Schiechtl & Stern, 1997).

Willows have ranges of ecological tolerance that can limit their use at particular sites: they are not very tolerant of shade (Schiechtl & Stern, 1997; Laing, 2003; Jarvis & Richards, 2008); their root systems are wide-spreading but will penetrate to a great depth only in permeable loose soil; willows do not tolerate dense grass cover; they have a high moisture demand (Anstead & Boar, 2010).

3.12.1.8 Climate Adaptation or Mitigation

The willow's dormant period over winter is becoming shorter due to climate change (Menzel, 2000). Frequent extreme weather conditions and high flows limited the suitability for willow installation. A solution may be the cold storage of the material. Li et al. (2005) found that willows stored at 4 °C in dark and moist conditions can be successfully planted.

3.12.1.9 Climate Factors / Constraints

No assessment.

3.12.1.10 Benefits and Trade-offs to Farmer/Land-manager

No assessment.

3.12.1.11 Uptake

No assessment.

3.12.1.12 Other Notes

None

4 KEY ACTION GAPS

5 EVIDENCE GAPS

6 REFERENCES

Abu-Zreig M, Rudra RP, Lalonde MN, Whiteley HR, Kaushik NK. Experimental investigation of runoff reduction and sediment removal by vegetated filter strips. Hydrological Processes 2004; 18: 2029-2037.Addy S, Cooksley S, Dodd N, Waylen K, Stockan J, Byg A, et al. River Restoration and Biodiversity: Nature-based solutions for restoring rivers in the UK. CREW, Republic of Ireland.

AHDB (2021) Nutrient Management Guide (RB209) https://ahdb.org.uk/nutrient-management-guide-rb209

Bhogal A, White C and Morris N. (2020). Maxi Cover Crop: Maximising the benefits from cover crops through species selection and crop management. AHDB Project Report No. 620.

Bernhard, A. E., Marshall, D., & Yiannos, L. (2012). Increased variability of microbial communities in restored salt marshes nearly 30 years after tidal flow restoration. Estuaries and Coasts, 35, 1049-1059.

Bernhard, A. E., Dwyer, C., Idrizi, A., Bender, G., & Zwick, R. (2015). Long-term impacts of disturbance on nitrogen-cycling bacteria in a New England salt marsh. Frontiers in Microbiology, 6, 46.

Borin M, Bigon E, Zanin G, Fava L. Performance of a narrow buffer strip in abating agricultural pollutants in the shallow subsurface water flux. Environmental Pollution 2004; 131: 313-321.

Boucard TK, McNeill C, Bardgett RD, Paynter CD, Semple KT (2008) The impact of synthetic pyrethroid and organophosphate sheep dip formulations on microbial activity in soil. Environmental Pollution 153, 207-214.

Bowler D, Mant R, Orr H, Hannah D, Pullin A. What Are the Effects of Wooded Riparian Zones on Stream Temperature? Environmental Evidence 2012; 1. https://www.researchgate.net/publication/235692845_What_Are_the_Effects_of_Wooded_Riparian_Zones_on_Stream_Temperature

Brentrup F, Lammel J. Stephani T and Christensen B (2018) Updated carbon footprint values for mineral fertilizer from different world region. Proceedings of the 11th International Conference on Life Cycle Assessment of Food 2018 (LCA Food) 17-19 October 2018, Bangkok, Thailand

Bullock JM, McCracken ME, Bowes MJ, Chapman RE, Graves AR, Hinsley SA, et al. Does agri-environmental management enhance biodiversity and multiple ecosystem services?: A farm-scale experiment. Agriculture, Ecosystems & Environment 2021; 320: 107582.

Burgess-Gamble L, Ngal R, Wilkinson M, Nisbet T, Pontee N, Harvey R, et al. Working with Natural Processes – Evidence Directory. Environment Agency, Bristol, 2018.

Card, S. M., & Quideau, S. A. (2010). Microbial community structure in restored riparian soils of the Canadian prairie pothole region. Soil Biology and Biochemistry, 42(9), 1463-1471.

Cardenas L.M., Thorman, R. Ashlee, N., Butler, M., Chadwick, D.R., Chambers, B.J., Cuttle, S.P., Donavan, N., Kingston, H., Lane, S., Dhanoa, M.S., Scholefield, D. (2010). Quantifying annual N2O emission fluxes from grazed grassland under a range of inorganic fertiliser nitrogen inputs. Agriculture, Ecosystems & Environment Volume 136, Issues 3–4, pp 218-226

Chambers, B. J., Smith, K. A. & Pain, B. F. (2000). Strategies to encourage better use of nitrogen in animal manures. Soil Use Manage. 16, 157-161.

Chambers, B. J., Smith, K. A. & Pain, B. F. (2000). Strategies to encourage better use of nitrogen in animal manures. Soil Use Management. 16, 157-161.

Collins KE, Doscher C, Rennie HG, Ross JG. The Effectiveness of Riparian 'Restoration' on Water Quality-A Case Study of Lowland Streams in Canterbury, New Zealand. Restoration Ecology 2013; 21: 40-48.

Cross P, Edwards-Jones G, Omed H, Williams AP (2010) Use of a Randomized Response Technique to obtain sensitive information on animal disease prevalence. Preventive Veterinary Medicine 96, 252-262.

Davies, D.B., Garwood, T.W.D and Rochford, A.D (1996) Factors affecting nitrate leaching from a calcareous loam in East Anglia. Journal of Agricultral Science Vol 128 pp 75-86

Defra (2018) British Survey of Fertiliser Practice https://www.gov.uk/.../british-survey-of-fertiliser-practice-2018

Defra (2019) Farm Practices Survey October 2019 – General - GOV.UK (www.gov.uk)

Defra (2021) Create and use a nutrient management plan - GOV.UK (www.gov.uk)

Defra project WQ0140 Competitive Maize Cultivation with Reduced Environmental Impact

Defra project WQ0932. Pollutant losses following organic manure applications in the month following the end of the closed period

de Snoo GR, de Wit PJ. Buffer Zones for Reducing Pesticide Drift to Ditches and Risks to Aquatic Organisms. Ecotoxicology and Environmental Safety 1998; 41: 112-118. Feld CK, Fernandes MR, Ferreira MT, Hering D, Ormerod SJ, Venohr M, et al. Evaluating riparian solutions to multiple stressor problems in river ecosystems — A conceptual study. Water Research 2018; 139: 381-394.

Fuentes- Rodríguez, F., Juan, M., Gallego, I., Lusi, M., Fenoy, E., León, D., Peñalver, P., Toja, J. and Casas, J.J. (2013), Diversity in Mediterranean farm ponds: trade-offs and synergies between irrigation modernisation and biodiversity conservation. Freshwater Biology, 58: 63-78.

Godshalk, G. L., & Wetzel, R. G. (1978). Decomposition of aquatic angiosperms. III. Zostera marina L. and a conceptual model of decomposition. Aquatic Botany, 5, 329-354.

Hanson, R. S., & Hanson, T. E. (1996). Methanotrophic bacteria. Microbiological reviews, 60(2), 439-471.

Hartman, W. H., Richardson, C. J., Vilgalys, R., & Bruland, G. L. (2008). Environmental and anthropogenic controls over bacterial communities in wetland soils. Proceedings of the national academy of sciences, 105(46), 17842-17847.

Heckrath G, Brookes P C, Poulton P R and Goulding K W T. (1995). Phosphorus leaching from soils containing different phosphorus concentrations in the broadbalk experiment. Journal of Environmental Quality, 24, 904–910.

Ibekwe, A. M., Lyon, S. R., Leddy, M., & Jacobson-Meyers, M. (2007). Impact of plant density and microbial composition on water quality from a free water surface constructed wetland. Journal of applied microbiology, 102(4), 921-936.

Johnson PW, Boray JC, Dawson KL (1992) Resistance to synthetic pyrethroid pour-on insecticides in strains of the sheep body louse Bovicola (Damalinia) ovis. Australian Veterinary Journal 69, 213-217.

Jonsson B, Jonsson N. A review of the likely effects of climate change on anadromous Atlantic salmon Salmo salar and brown trout Salmo trutta, with particular reference to water temperature and flow. Journal of fish biology 2009; 75: 2381-447

Kay, D. Crowther, J., Stapleton, C.M., and Wyer, M.D. (2018). Faecal indicator organism inputs to watercourses from streamside pastures grazed by cattle: Before and after implementation of streambank fencing. Water Research Vol 33 pp 229-239.

Kleinman, P.J.A., Bryant, R.B., Reid, W.S., Sharpley, A.N., and Pimentel, D. (2000). Using soil phosphorus behaviour to identify environmental threshold. Soil Science, 165, 943-950.

Lord, E. and Mitchell, R. (1998). Effect of nitrogen inputs to cereals on nitrate leaching from sandy soils. Soil Use and Management, 14, 78-83

McCall SJ, Hale MS, Smith JT, Read DS, Bowes MJ. Impacts of phosphorus concentration and light intensity on river periphyton biomass and community structure. Hydrobiologia 2017; 792: 315-330.

Mckiernan F, O'Connor J, Minchin W, O'Riordan E, Dillon A, Harrington M, Zintl A (2021) A pilot study on the prevalence of lice in Irish beef cattle and the first Irish report of deltamethrin tolerance in Bovicola bovis. Irish Veterinary Journal 74, 20.

Muirhead, R.W. (2019) The effectiveness of streambank fencing to improve microbial water quality: A review. Agricultural Water Management Vol 233. https://doi.org/10.1016/j.agwat.2019.105684

Muscutt AD, Harris GL, Bailey SW, Davies DB. Buffer Zones to Improve Water-Quality - a Review of Their Potential Use in Uk Agriculture. Agriculture Ecosystems & Environment 1993; 45: 59-77.

Nair, V.D., Portier, K.M., Graetz, D.A. and Walker, M.L. (2004). An environmental threshold for degree of phosphorus saturation in sandy soils. Journal of Environmental Quality, 33, 107-113.

Newell Price, J.P., Harris, D., Taylor, M., Williams, J.R., Anthony, S.G., Duethmann, D., Gooday, R.D., Lord, E.I. and Chambers, B.J. Chadwick, D.R. and Misselbrook, T.H. (2011). An Inventory of Mitigation Methods and Guide to their Effects on Diffuse Water Pollution, Greenhouse Gas Emissions and Ammonia Emissions from Agriculture. Defra Project WQ0106

Nicholls, R. J., Hoozemans, F. M., & Marchand, M. (1999). Increasing flood risk and wetland losses due to global sea-level rise: regional and global analyses. Global Environmental Change, 9, S69-S87.

Nicholson, F.A., Bhogal, A., Chadwick, D., Gill, E., Gooday, R.D., Lord, E., Misselbrook, T., Rollett, A.J., Sagoo, E., Smith, K.A., Thorman, R.E., Williams, J.R. and Chambers, B.J. (2013). An enhanced software tool to support better use of manure nutrients: MANNER-NPK. Soil Use and Management 29, 473-484.

Nix, J. (2020) John Mix Pocket Book for Farm Management. (50th Edition)

OECD (2022), "Nutrient balance" (indicator), https://doi.org/10.1787/82add6a9-en (accessed on 25 February 2022).

Paerl HW, Huisman J. Climate - Blooms like it hot. Science 2008; 320: 57-58.

Thomas SM, Griffiths SW, Ormerod SJ. Beyond cool: adapting upland streams for climate change using riparian woodlands. Glob Chang Biol 2016; 22: 310-24.

Poulton P R, Johnston A E and White R P (2013). Plant-available soil phosphorus: part I: the response of winter wheat and spring barley to Olsen P on a silty clay loam Soil Use and Management. 29 4–11

Reyne, M., Nolan, M., McGuiggan, H., Aubry, A., Emmerson, M., Marnell, F., & Reid, N. (2021). Artificial agri-environment scheme ponds do not replicate natural environments despite higher aquatic and terrestrial invertebrate richness and abundance. Journal of Applied Ecology, 58(2), 304-315.

SRUC (2011) Control of Sheep Scab and other Ectoparasites of Sheep https://www.sruc.ac.uk/media/datc4bjs/tn636-sheep-scab.pdf (accessed 14/2/2022)

Thiere, G., Milenkovski, S., Lindgren, P. E., Sahlén, G., Berglund, O., & Weisner, S. E. (2009). Wetland creation in agricultural landscapes: biodiversity benefits on local and regional scales. Biological conservation, 142(5), 964-973.

Thomas SM, Griffiths SW, Ormerod SJ. (2016). Beyond cool: adapting upland streams for climate change using riparian woodlands. Global Change Biology 22, 310-324.

Urakawa, H., & Bernhard, A. E. (2017). Wetland management using microbial indicators. Ecological Engineering, 108, 456-476.

Virtue WA, Clayton JW (1997) Sheep dip chemicals and water pollution. Science of the Total Environment 194–195, 207-217.

Williams, J.R. Rose, S.C and. Harris. G.L (1995). The impact on hydrology and water quality of woodland and set-aside establishment on lowland clay soils. Agriculture Ecosystems and Environment 54 215-222

Withers, P.J.A., Hodgkinson, R.A., Rollett, A., Dyer C., Dils, R., Collins, A.L., Bilsborrow, P.E., Bailey, G. and Sylvester-Bradley, R. (2017). Reducing Soil Phosphorus Fertility Bring Potential Long-term Environmental Gains: A UK Analysis. Environmental Research Letters, 12, 1-20