Evidence Base Development for Nature-Based Nutrient Mitigation Solutions – Literature Review

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Foreword

Natural England commission a range of reports from external contractors to provide evidence and advice to assist us in delivering our duties. The views in this report are those of the authors and do not necessarily represent those of Natural England.

This report was commissioned by Natural England to build knowledge and understanding on a range of nature-based solutions which potentially could be used to reduce nutrients. Ricardo was commissioned by Natural England to understand the mechanisms of nutrient removal for the different solutions, the factors which affect this and review the evidence on the scale of nutrient reductions that they could achieve. This final report presents the outcomes of the literature review and provides recommendations for precautionary nutrient reduction efficiency values, where there was sufficient evidence to determine these, which could be used in the assessment of nutrient neutrality mitigation schemes.

1. Executive summary

The objective of this project is to provide support to Natural England (NE) employees and those of other relevant organisations (such as Competent Authorities) to enable them to make informed judgements on Nature-based Solutions (NbS) proposals for nutrient mitigation. This report takes the form of a literature review, through which nutrient removal efficiency percentages have been calculated to apply to both nitrogen (N) and phosphorus (P) for NbS to achieve nutrient neutrality (NN), where possible. The literature review underpins the methodologies and outputs for the rest of this project, which comprises three parts where:

- **Part 1** (this report known from now on as the literature review) provides the evidence base on the effectiveness of four different NbS for nutrient mitigation including the methodology applied.
- **Part 2** (The Framework – separate documents) considers the design, implementation, monitoring and maintenance needs and how to determine an upfront scheme specific nutrient reduction (where applicable). There are four framework documents one for each of the four mitigation solutions considered in part 1.
- **Part 3** (the lookup tool – separate spreadsheet) comprises a user-friendly lookup tool with high-level practical information on a wider range of potential nutrient mitigation solutions.

The literature review outlines the sources of N and P and the nutrient removal processes within the natural environment. From combining this research, indications of the possible nutrient removal capacity of different NbS have been provided. For riparian buffer strips only, precautionary nutrient removal percentage estimates have been calculated for both N and P. These percentages can be used to determine scheme specific efficiency values which can be claimed upfront as set out in **Part 2** (The Framework). For river channel re-naturalisation, engineered logjams and agroforestry systems, however, percentage efficiency values have not been calculated as there is not enough evidence to provide an upfront figure. For these schemes, monitoring pre- and post-implementation is required to understand the likely site-specific nutrient load reduction which is occurring as a result of implementing the scheme.

Total Phosphorous (TP) refers to the amount of P removal being measured. Total Nitrogen (TN) and Nitrate are the key forms of N removal being measured. The headline figures from this literature review are outlined as follows:

NbS	Forms of N and P	N removal efficiency (%)	P removal efficiency (%)
Riparian buffers	Nitrate, TP	10-36% depending on width	22-43% depending on width
River channel re-naturalisation	TN, TP	Monitoring required	Monitoring required
Engineered logjams	TN	Monitoring required	N/A[1]
Silvopasture	Nitrate, TP	Monitoring required	Monitoring required
Silvo-arable	Nitrate, TP	Monitoring required	Monitoring required

The figures provided for riparian buffers are highly precautionary, therefore in the instance that a scheme is well designed with the principles of NN in mind, it is likely that pre- and post-implementation monitoring will evidence a scheme to be removing nutrients to a greater extent that the precautionary values suggest. In this scenario, additional credits can be claimed if a robust monitoring scheme is in place to evidence the additional nutrient reduction. For further details on credit generation, see **Part 2** (The Framework).

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[1] Due to the short-term nature of the P removal processes for Engineered Logjams they cannot be suggested as suitable mitigation solutions for P.

Table of Contents

2. Introduction

Internationally important wildlife conservation sites, referred to as Habitat sites that encompass Special Protection Areas (SPAs), Special Areas of Conservation (SAC) and Ramsar sites, are protected under Water Environment Regulations (Water Framework Directive) and The Conservation of Habitats and Species Regulations 2017 (as amended, hereafter referred to as the Habitats Regulations). Numerous Habitat sites are found in freshwater and coastal environments and are under pressure due to nutrient enrichment and associated eutrophication problems. These problems can be primary reasons for a Habitat site being in unfavourable condition.

Despite legislative requirements to try and reduce nutrient loading and associated impacts in sensitive waters, nitrogen (N) and phosphorous (P) levels remain high in many Habitat sites. As such, there are many Habitat sites in England that are in unfavourable condition due to excess N and/or P loading and its related impacts. Sources of N and P to these sites are predominantly either from agricultural diffuse pollution or come from point source, treated wastewater discharges.

The November 2018 ruling by the Court of Justice of the European Union (CJEU), referred to as the Dutch N Case or Dutch Case, ruled that increased atmospheric N deposition to Dutch Habitat sites resulting from new projects and plans may pose a risk to “site integrity” due to the link between nutrient enrichment and eutrophication. Following this ruling, Natural England (NE) now considers that the CJEU judgement applies to increased nutrient loading to Habitat sites in England and therefore competent authorities need to consider the risk of significant impacts that could arise from plans or projects that increase nutrient inputs to Habitat sites.

NE’s legal advice on Nutrient Neutrality made clear that nutrient loading impact pathways would need to be screened into a Habitats Regulations Assessment (HRA) for new developments that could increase nutrient discharge to Habitat sites. Each new development that increases the number of overnight stays and thus increases the production of wastewater and associated nutrient loading by *any amount* to Habitat sites already in unfavourable condition due to nutrient loading may not be legally consented. Following the People Over Wind ruling of the CJEU, mitigation measures cannot be incorporated at the screening stage of an HRA (Stage 1) and so new developments can be screened into an HRA Stage 2 Appropriate Assessment (AA) due to “likely significant effects” on Habitat sites resulting from increases in nutrient loads from the development. An AA can incorporate mitigation measures into its assessment of adverse effects on conservation sites. In order to assess the requirement of a housing development for mitigation of the nutrient loading impact pathway, NE requires developers/Local Planning Authorities (LPAs) to produce a nutrient budget for the development. If the nutrient budget shows the development will result in an increase in N or P coming from the development compared with the current land use, mitigation will be required to ensure the development is “nutrient neutral”.

There are range of potential mitigation options that can be used to secure nutrient neutral development. These options can broadly be categorised into engineered and nature-based solutions (NbS). Engineered solutions include measures such as upgrading wastewater treatment works (WwTWs) which are not the focus of this review. NbS encompass a wide array of different measures, which include constructive wetlands, Sustainable Drainage Systems (SuDS) and catchment-based land use and river management. This review has focussed on catchment management NbS to determine the potential of a range of measures for achieving nutrient mitigation with sufficient certainty to be adopted as part of nutrient mitigation strategies to achieve nutrient neutral development.

This report provides the outputs from a literature review on catchment management NbS in order to identify whether there are solutions that have a sufficient evidence base to a) support the scientific principles that show a solution will deliver nutrient mitigation; and b) determine whether each studied measure can have a percentage nutrient removal estimate derived from the literature, as this will support the deployment of measures by allowing quantification of what they will deliver before they have been deployed. The review has also identified knowledge gaps in the literature that should be considered in order to assist with recommending NbS for nutrient mitigation. Additional to the review of NbS for nutrient mitigation, this review has also assessed whether there is a sufficient evidence base to support habitat-specific nutrient export coefficients for use in determining the background nutrient export that will remain following agricultural land use conversion mitigation schemes.

3. Project aims and objectives

The overall objective of this project is to provide a support to NE employees and those of other relevant organisations (such as Competent Authorities) to enable them to make informed judgements on Nature-based Solutions (NbS) proposals for nutrient mitigation. It consists of 3 parts where:

- **Part 1** (this report known from now on as the literature review) provides the evidence base on the effectiveness of four different NbS for nutrient mitigation including the methodology applied;
- **Part 2** (The Framework – separate documents) considers the design, implementation, monitoring and maintenance needs and how to determine an upfront scheme specific nutrient reduction (where applicable). There are four framework documents, one for each of the four mitigation solutions considered in part 1.

- **Part 3** (the lookup tool - separate spreadsheet) comprises a user-friendly lookup tool with high-level practical information on a wider range of potential nutrient mitigation solutions.

To form the evidence base required for the rest of the project, this report used a literature review to first describe the overarching factors and processes that remove nutrients in semi-natural habitats and NbS (Section 5).

The process review was used as a reference point to highlight the different processes that remove nutrients in the NbS that were assessed in this study. A review of export coefficients from semi-natural habitats was conducted in order to determine if values specific to different habitat types could be derived from the literature (Section 6).

This analysis was aimed at providing more specific background export coefficients that could be used for different semi-natural habitat types that may be the target for restoration on previously agricultural land that has been converted to deliver nutrient mitigation. The assessment of literature on the nutrient removal potential of different NbS was used to compile an evidence base for each mitigation solution (Section 7).

The assessment of each solution aimed to confirm the scientific principles that evidence a given solution can provide N and P, as well as what key factors affect nutrient removal potential. The review also sought to determine whether a percentage nutrient removal efficiency could be determined for each reviewed NbS. The factors that affect the efficiency of nutrient removal in a given solution were also assessed in order to highlight key design considerations that will be used to support **Part 2** (The Framework) by providing guidance for best practice implementation. This report focusses specifically on the nutrient mitigation potential of different mitigation solutions. It should be noted that the considerations on how each reviewed NbS functions are specific to nutrient mitigation and other factors may be more important if an NbS is being designed to maximise a different outcome, such as Biodiversity Net Gain or carbon sequestration.

4. Methodology

4.1 Literature review

This study has used a literature review to compile data on the effectiveness of NbS for providing nutrient mitigation for aquatic ecosystems. The data compiled through this review has formed an evidence base that will be used to provide guidance on how NE staff can assess proposals for nutrient mitigation solutions to help new development achieve nutrient neutrality. To align the outputs from this review with the outputs from nutrient budgets for new developments, which show an amount of N or P that needs mitigating in kg/yr, literature was reviewed to determine if it is possible to derive estimates of the percentage efficiency of different NbS for nutrient mitigation. If robust percentage efficiencies for mitigation effectiveness can be derived, they can be applied to estimates of nutrient loads entering a mitigation solution to provide an estimate of load reduction (in kg/yr) that a mitigation solution can support.

It is known that the efficiency of NbS for nutrient mitigation is influenced by different environmental and design factors. Thus, the literature has aimed to answer the following two research questions:

1. Can robust estimates be derived for the percentage efficiency of N and P removal for different types of NbS related to nutrient mitigation?

2. What key factors influence the percentage efficiency of nutrient removal for a given type of NbS?

A set of NbS were chosen for assessment through consultation with NE and these solutions were assessed for their ability to effectively mitigate nutrient pollution through the removal of N and P. The pollutant removal capacity of these solutions can be highly variable as it is dependent on the source of N and P and the removal processes that are active in a given NbS, as well as local environmental factors.

The final list of NbS chosen for assessment were solutions that are likely to foster nature-based processes to mitigate nutrient pollution through changes to land and river management. Solutions using hard engineering techniques were not included in this study.

It should also be noted that NE has commissioned two parallel studies on nutrient mitigation using wetlands and SuDS. To avoid overlap with these studies, neither of these NbS were included in this study.

Following consultation with NE, the solutions identified for inclusion in this review have been broadly classed as habitat restoration of degraded habitats which, when restored, can provide nutrient mitigation. These include:

- **River channel re-naturalisation:** In the context of this work river channel re-naturalisation is defined as overarching approaches to creating more natural river forms and processes and enhance connectivity to the floodplain where feasible. These approaches are a specific subset of the wider toolbox of river restoration techniques.

- **Riparian buffers:** These also often considered as a river restoration technique but are generally delivered in specific catchment and river types where there is either a) farming that may encroach close to the river edge and/or b) areas where full scale process-driven restoration is not feasible.

- **Engineered logjams:** These are generally seen as either a subset of a way of blocking upstream drainage ditches or to create flow diversity in rivers where such features have been removed by previous management, by restoring natural river fluctuations using biomimicry. We have considered both engineered logjams and logjams created by beavers as they both result in the same processes of nutrient removal and thus evidence from studies of beaver dams can provide useful proxies for the impacts of engineered logjams on nutrient removal.

- **Agroforestry** is a collective name for land use systems and technologies where woody perennials are introduced to land that is also used for arable or livestock farming. Growth of trees within the agricultural landscape helps to reduce nutrient export from agriculture.

Each of these and their potential benefits for Nutrient Neutrality are discussed in more detail in Section 7 of this report.

Additionally, research was conducted to determine the veracity of the current natural background N and P export coefficients used in nutrient budget calculations. They are employed to estimate the long-term nutrient exports from mitigation schemes that convert agricultural land to semi-natural habitats. As such, it is important to understand whether the background nutrient export coefficients that are currently used for semi-natural land uses are based on the best available evidence.

For each of the above NbS, relevant literature and data were acquired from a search and review of both academic publications and grey literature. Searches were undertaken via the following search engines: Google Scholar, Google and Jstor. Search engines were searched using search strings that combined the above NbS with search terms relevant to nutrient mitigation. For example, the name of an NbS such as ‘buffer strips’ was combined with terms such as ‘pollution retention’, ‘nutrient retention’ and ‘nitrogen removal’ / ‘phosphorus removal’. The following metadata for each search have been recorded:

- Search engine used.

- Search string entered into search engine.

- Title of document(s) found.

- URL for the location of a document.

- Brief synopsis of the document.

These metadata are recorded in a spreadsheet which is provided in Appendix 1.

For each the NbS listed above, different variables were extracted from the relevant literature. These were based on the factors assumed to influence nutrient retention capacities of each NbS. These assumptions stem from background research conducted to better understand the requirements of the study and from previous research conducted into mitigation measures conducted on other projects e.g.(Ricardo, 2021b). Variables were either environmental (e.g. soil type), methodological (e.g. no. of samples) or related to types of measurement (e.g. type of N or P). The variables assessed across literature for all types of NbS reviewed in this study are detailed in Table 4:1.

Table 4:1. Variables assessed in all studies of nutrient mitigation for the chosen types of NbS.

Environmental variables	Methodological variables	Measurement types
• Soil type • Geology • Vegetation type/presence • Geographical location of the study • Location of the solution within the catchment	• Does study account for seasonality? • Replicability • No. of samples • Length of sampling period • Date of study	• Type of N and P, e.g. nitrate, phosphate, total nitrogen total phosphorus etc. • Units • How results were reported, e.g. averages only, averages with ranges etc.

Certain additional variables were identified for consideration that are specific to each of the NbS listed above (Table 4:2). Agroforestry practices were divided into ‘silvo-pasture’ and ‘silvo-arable’, however both had similar additional variables recorded in these studies and thus they were grouped under the agroforestry NbS type. For several NbS, additional variables were added during the review of literature and data. For example, the tree density was included when reviewing agroforestry literature.

Table 4:2. Additional variables extracted for assessment of specific types of NbS for nutrient mitigation.

NbS type	Additional variables
River channel naturalisation	• Type of riverbed substrate
Riparian buffers	• No. of sampling zones

NbS type	Additional variables
	Sample locations Width Gradient
Agroforestry	Sample locations Gradient Tree density Grazing density Root depth
Engineered logjams	Blocking/dam material

Assessment of the outputs for each of the variables detailed in Table 4:1 and Table 4:2 were used to determine whether it was possible to provide answers to the research questions detailed above. Methodological variables were used to determine whether a given study was suitable for use in this research, i.e. could it be used to determine a robust estimate of nutrient removal efficiency for a given NbS? Studies that lacked clarity on their methodology or that had methodological flaws to the approach used to derive nutrient reduction potential were excluded from the review. Studies were rejected based on various criteria, including number of samples taken, length of sampling programme, sampling design and whether they accounted for seasonality. Table 4:3 provides an explanation for the methodological criteria used to include studies in estimates of percentage efficiency of nutrient removal. In instances where the criteria were not met, the study was rejected from the literature review and not recorded.

Table 4:3. Explanation of the criteria required for a study to be included within the literature review

Study Inclusion Criteria	Required Content
Relevant Subject	Nutrient removal efficiency of a given mitigation solution
Type of NbS	Implementation of riparian buffers, agroforestry, engineered logjams or river channel re-naturalisation

Study Inclusion Criteria	Required Content
Type of Comparator	Clear explanation of monitoring pre- and post-implementation, above and below the solution, or with reference to a suitable control site with relevant environmental conditions
Outcome	Removal (or addition) of nutrients in kg/ha/year or %
Form of N and P monitored	Measurement of nitrate, TN, DIN and TP (studies rejected only at the end of the literature review, to allow for identification of the most common units)
Length of Sampling Period	Study must have a sampling period of longer than a year, in order to try and account at least for seasonal variation and preferably longer-term variability in nutrient removal.
Replicability	Replicable methodology with rationale behind monitoring design.
Real-life Experimentation	Evidence of field experimentation, as opposed to modelling

Data for every variable was not always provided by each study reviewed, thus it should be noted that for each NbS the volume and detail of data available varied. A lack of all desired variables did not deem the study unsuitable, however, providing all the criteria in Table 4:3 was met. The limitations placed on the compiled dataset resulted in certain limitations to the analysis which could be undertaken for each mitigation solution, which is detailed for each NbS in the analysis presented below.

Different studies reported nutrient removal results for varying types of N and P. This created problems when comparing, for example, the nutrient removal efficiencies detailed in two studies where one study reported results for nitrate removal and the other reported results for total nitrogen (TN). Where nutrient removal percentages were available, studies for P were used that reported results in total P (TP) and TN was the main focus for N (See

Table 4:3)[2]. These were chosen due to the quantity of available literature for the different types of N and P.

Though the main focus for N was TN, it is worth noting that other forms of inorganic and organic N are present in water entering a NbS. As such, papers reporting percentage removal efficiencies in various forms of N were also included where these types of N were reported in the literature.

4.2 Percentage removal calculations

The literature review resulted in the formation of a database containing percentage nutrient removal efficiencies demonstrated in a variety of studies for each different mitigation solution. The database was deemed unsuitable to calculate precautionary percentage nutrient reductions for river channel re-naturalisation, engineered logjams and agroforestry schemes. For these NbS the key findings from the literature review alone make up the evidence base which supports the use of these mitigation measures as solutions for removing nutrients from the environment. This methodology therefore precludes an estimate of nutrient efficiency without requiring monitoring for all NbS other than riparian buffer strips[3].

5. Nitrogen and phosphorus removal processes in nature-based solutions

To provide the background information required to ultimately establish nutrient reduction estimates and design considerations required for each NbS, the following sections provide an overview of:

- The main input sources of N and P (see Section 5.1).
- The processes occurring within the selected NbS which actively remove nutrients from the system (see Sections 5.2 - 5.5).

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[2] Nitrate was focused on for silvopasture and silvo-arable as it is expected that FarmScoper will be used to model nutrient loading to agroforestry schemes. The percentage efficacy values obtained for N must be nitrate to remain consistent with FarmScoper's outputs.

[3] The precautionary estimates of Nitrate and TP removal efficiencies for riparian buffers have been derived by Entrade and ARUP and set out in the Interim Nutrient Reduction standard (ARUP and Entrade, 2022).

- The additional factors influencing the efficiency of these processes (See Sections 5.2 – 5.5).

These sections provide context for the latter sections which assess the efficacy of the chosen NbS and will be referred back to in these sections in order to highlight the processes that drive nutrient removal within a given NbS.

5.1 Nitrogen phosphorus and sources

Human activities have significantly altered N and P cycles through increasing the nutrient concentration of run-off entering waterways. Inputs of N and P can originate from a variety of sources including agriculture, wastewater, sewer overflows, urban runoff, atmospheric deposition, and industry. Agricultural production and urban wastewater treatment plants have been identified as two of the main diffuse and point-source inputs of nutrient pollution to aquatic environments (White & Hammond, 2008). Both sources contribute comparably high loads of N and P into downstream waterways, resulting in reduced water quality and in some cases eutrophication. The total and relative contributions from each source varies between catchments.

5.1.1 Sewage treatment works

WwTWs process the wastewater that is produced in domestic and commercial settings. This wastewater contains nutrients from human waste, tap water, food, soaps and detergents.

From the perspective of nutrient pollution, WwTWs can be broadly divided into two types:

- Those with nutrient stripping technologies and associated nutrient permits and;
- Those without nutrient stripping and nutrient permits.

All WwTWs will discharge some excess N and P to the water environment, however WwTWs without nutrient stripping result in much greater nutrient loading to their receiving waterbodies. In WwTWs without nutrient stripping, the natural processes that are active either in activated sludge or biofiltration treatment will remove some of the influent load of nutrients, but the effluent concentrations are still often very high relative to concentrations found in healthy aquatic ecosystems. WwTWs will also output N and P in various forms, however ammonium and nitrate are the predominant forms of N found in WwTW effluent whilst orthophosphate is dominant form of P.

5.1.2 Agriculture

Nutrient sources from agricultural land can come from decomposing plants and animal waste that leach into soils or remain on the soil surface and are subsequently transported via sub-surface flow pathways or surface runoff to nearby waterbodies. Excess N and P from fertilisers that are not assimilated by plants are also a large source of nutrient pollution from the agricultural environment. Agricultural nutrient export is generally exacerbated by heavy rainfall. Unlike WwTW, the inputs from which remain relatively constant throughout the year, agricultural inputs vary throughout the year due to seasonal changes in rainfall intensity and differing rates of fertiliser application. This can often be reflected by short-term changes in nutrient concentrations within waterbodies. In chalk catchments, however, where river flows are groundwater dominated, changes to N concentrations in waterbodies can be unpredictable due to the potential for nutrient pollution to be temporarily stored in aquifers. Due to the nature of aquifers, the nutrients can be remobilised, causing significant lag times between nutrients being released into the environment and entering surface waterbodies.

N in fertiliser often can either be in the form of ammonium or nitrate, with ammonium fertilisers often cycling quickly to nitrate under the right soil conditions. P fertilisers generally comprise various forms of phosphate, but organic sources of both N and P can also leach from agricultural environments through the application of organic fertilisers such as animal manure.

5.1.3 Types of N and P

There are several forms in which both N and P are exported from agricultural land uses and WwTWs. These can be broadly classed as dissolved inorganic, dissolved organic, particulate organic and particulate inorganic. The type of N or P exported from a given source will impact the processes that can act to remove nutrients from the environment. For each source, the ratio of each type of N and P exported varies. P exported in sewage effluent and subsurface flow pathways from the land surface comes mostly in dissolved forms such as orthophosphate or is bound to organic matter (OM) (Environmental Agency, 2019), whereas surface runoff may contain a higher proportion of particulate forms of P. N compounds bind much less readily to sediments, with ammonium adsorption as the key process of ammonium retention by sediments and accounting for a small proportion of N removal within the environment (Mancuso and others, 2021). Ammonium and nitrate are the dominant forms of N exported in treated wastewater whilst inorganic forms of nitrate tend to be the dominant form of N in agricultural exports. Dissolved organic and inorganic N leaching into groundwater has also been recognised as an important lagged pathway for sources of N from agricultural systems to reach surface water environments.

5.2 Phosphorus removal through precipitation and sediment deposition

P removal can occur along surface water flow pathways in the terrestrial environment and through a range of processes once P has entered aquatic ecosystems. In both terrestrial and aquatic environments, P can be immobilised via chemical precipitation as well as sediment deposition. Precipitation of dissolved P can occur through reactions with metal ions. These reactions cause P in solution to form phosphate minerals which precipitate out of solution and render the P inaccessible to plants (Reddy and others, 1998). On surface water runoff pathways, this process often occurs as co-precipitation with calcium (Ca), though this process is relatively limited and thus does not regulate sources of P to rivers by immobilising P within the terrestrial environment (Mainstone & Parr, 2002). In aquatic environments, co-precipitation reactions occur under the presence of aluminium (Ai), iron (Fe) or Ca to form mineralised P precipitates that are inaccessible to plants. P precipitation is heavily affected by temperature and pH, alongside a range of other environmental conditions, which means this process is highly seasonal (Mainstone & Parr, 2002). Additionally, over periods of many years, dissolution can occur whereby the insoluble P precipitate is released back into solution, becoming bioavailable again (Johnston & Dawson, 2005). For precipitation to occur where organic P sources dominate, there is a need for particulate organic P to enter the dissolved phase and for the dissolved organic P fraction to be cleaved into dissolved inorganic P.

The other key removal process in terrestrial and aquatic environments is the deposition of sediment-bound P. Increased terrestrial surface roughness caused by variations in vegetation types and especially by larger, woody vegetation reduces surface runoff velocities, reducing the energy available for sediment transportation (Environment Agency, 2015). In rivers, sedimentation is mainly dependent on channel heterogeneity and the associated hydraulic factors that slow flow, thus reducing flow energy and sediment transport capacity. This results in the deposition of particulates and their adsorbed P load, immobilising P within the environment. This mechanism of P removal may only be a temporary solution as resuspension of sediment is possible during period of heavy rainfall and associated surface water runoff and high flows in rivers, and through aeolian transport of sediment-bound P (Reddy and others, 1998). If deposited P desorbs from the sediment and enters the soil solution, it may be taken up by vegetation, removed by cropping and hence immobilised for a longer period of time (Schachtman and others, 1998).

Table 5:1. Summary of conditions required for P precipitation and deposition to occur

Removal process	Summary of conditions	References
Optimal conditions for P precipitation	• High availability of dissolved iron, aluminium, manganese (in acid soils), or calcium (in alkaline soils) • pH higher than 7 • High soluble P concentrations in water	• Cornell University (2006) • Mainstone and Parr (2002)

Removal process	Summary of conditions	References
Optimal conditions for P deposition	• High surface roughness caused by variation in vegetation types, for example • Low energy water flows • High availability of sediment bound P relative to transport capacity of surface water or channel flows	• Environment Agency (2015)

5.3 Phosphorus removal through sediment and soil sorption

For removal to occur through sorption, surface water must infiltrate into soils, providing dissolved P a chance to bind to sediments. The infiltration capacity of riparian soils depends heavily upon rainfall intensity, gradient, surface roughness and soil porosity, as well as a range of other environmental variables (Khalid and others, 1977).

In aquatic environments, the infiltration capacity of sediments is more dependent upon bedforms, roughness elements and obstacles within a channel that result in advective processes that move water from the channel into the hyporheic zone (Brunke & Gonser, 1997). However, these processes will happen more readily in streams with more porous substrate, e.g. gravel. This movement of water into the hyporheic zone is termed transient storage, which can be defined as the temporary retention of stream water away from the main channel flow (Ensign & Doyle, 2005). Due to the importance of residence time for sediment sorption P removal processes, the duration of this transient storage in the hyporheic zone is very important in providing sufficient time for P sorption reactions to occur (Buss and others, 2009). When available P sorption sites in dissolved P molecules come into contact with soil, chemical sorption of P onto the sediment occurs quickly, whilst the physical process of P penetrating into soil particles can take days (Reddy and others, 1998). This slow phase of the sorption process requires the diffusion of P into the porous Ai- and Fe-oxides within soils and results in reduced lability of the adsorbed P. This combination of processes is termed adsorption and temporarily renders the P particle insoluble and inaccessible to plants.

Many factors affect the sorption capacity of soils and sediments. Soil type, for example, has a great influence on sorption, with certain soils such as Fe- and Ai-oxides having high specific surface areas (SSA). This makes them ideal adsorbents for P as they have a significant quantity of sorption sites with which to accumulate P (Reddy and others, 1998). Clay soils exhibit these characteristics most strongly. The OM content of soil is also important for understanding soil sorption capacities. OM can compete for sorption sites on the surface of soil particles, preventing sorption of P (Reddy and others, 1998). OM also has the capacity to alter the sorption sites, causing potential P leaching. The presence of OM in the soil also provides an energy source for bacteria, which promotes anoxic conditions via heterotrophic respiration which consumes oxygen to generate energy through the consumption of carbon. These anoxic conditions can further reduce the sorption capacities of P within sediments and soils by encouraging Fe bound P to become available to surrounding waters (Patrick, Jr & Khalid, 1974).

Additionally, the P content of sediments is important when compared to dissolved loads within terrestrial and aquatic flows. P sorption relies heavily upon equilibrium principles, allowing either sorption or desorption to occur depending upon the conditions (Jalali & Naderi Peikam, 2013). This is dependent upon the equilibrium P concentration (EPCo); the point at which the concentration of P in sediments and water is balanced and sediments act as neither a sink or a source of P to waterbodies (Lucci and others, 2010). If the dissolved P concentration of overlying water is greater than the EPCo of hyporheic and riparian sediments, sediments have the capacity to remove P surrounding water (Lucci and others, 2010). Conversely, when P in water is below the EPCo of surrounding sediments, P can desorb from soils and sediments, with sediments switching to a temporary source of P to the surrounding environment until EPCo has reduced to below that of surrounding water. When water is below the EPCo of sediments, a higher P concentration in water that is in contact with sediments will generally result in a faster sorption reaction time (Reddy and others, 1998). Additionally, longer contact times of water containing dissolved P with sediments tends to result in more effective P to be adsorption into soil and sediment particles to the point where it cannot easily be desorbed.

Additional to residence time, pH also strongly influences sorption capacities. A pH of 6-7 is the optimal range for plant uptake; lower than 6 and sediment adsorption is more likely, whereas at pH > 6 precipitation is possible (Reddy and others, 1998). Sorption capacity is thought to decrease under anaerobic conditions as well as high salt concentrations (Bai and others, 2017). Additionally, high temperatures are favourable for soil sorption processes to occur whereas at low temperatures soil pores can be blocked by ice, decreasing their P attenuation capacity and highlighting the impact of seasonal variation in conditions that effect P sorption processes (Haycock, 1997).

It is also worth noting that there is a limit to how much P soils can retain at which point the sorbed P may be re-released into the environment for onward transport or to be taken up by vegetation (Reddy and others, 1998). There is little research into the effects of P saturation in the context of nutrient mitigation solutions. However, it is understood that harvesting vegetation prolongs the longevity that soils and sediments can adsorb P by permanently removing P from the system (Panagos and others, 2022).

Table 5:2. Summary of conditions required for terrestrial and aquatic P sorption to occur

Removal process	Summary of conditions	References
Optimal conditions for P sorption	• High specific surface area of soils, providing significant sorption sites (e.g. clay soils) • Soil pH lower than 6 • Low OM content of soil and sediments • High oxygen availability in the soil • Warm conditions	• Khalid and others (1977) • Reddy and others (1998) • Cornell University (2006) • Patrick, Jr & Khalid (1974)
Optimal conditions for P sorption, exclusive to terrestrial environments	• High inorganic P concentration of overland and subsurface flows • High infiltration capacity of terrestrial soil (low gradient, high surface roughness, high soil porosity, low rainfall intensity)	• Khalid and others (1977) • Cornell University (2006)
Optimal conditions for P sorption, exclusive to aquatic environments	• High inorganic P concentration of channel flow • Significant duration of water held in transient storage, at the hyporheic interface	• Ensign & Doyle (2005)

5.4 Nitrogen removal through chemical and physical processes

The N cycle consists of many biogeochemical processes through which N is cycled between different chemical forms. These processes can occur in terrestrial, marine and freshwater ecosystems. As highlighted in Section 5.1, the primary sources of N are wastewater discharges and agriculture. The main forms of N in wastewater are organic N and ammonia. Both of these forms of N cycle through to nitrite and nitrate via nitrifying bacteria. Nitrate is then either bacterially denitrified or assimilated by plants to aid growth. The processes cycling ammonia to nitrate require oxygen, whereas denitrification is largely an anaerobic reaction. This shows the variety of conditions required to support N cycling and the associated removal of N from a given aquatic and terrestrial environment (Groffman and others, 2002).

Denitrification is the final step of the N cycle that results in removal of N from terrestrial and aquatic environments. As stated in Bradley and others (2011), it is a process which occurs at a microbial level whereby microbes “reduce” (by accepting electrons in cell respiration) and convert oxidised forms of N (nitrate and nitrite) to gaseous forms of N (nitric oxide (NO)), nitrous oxide (N_2O) and N gas (N_2). N_2 is the final product of denitrification and is released back into the atmosphere when dentification of nitrate is complete. However, interruptions to the conditions that support denitrification can result in incomplete denitrification and the release of NO or N_2O to the atmosphere (Bradley and others, 2011). NO and N_2O are powerful greenhouse gasses and so it is preferable for denitrification to complete the cycle back to N_2. Most organisms that are responsible for denitrification are bacteria and most of these bacteria are facultative aerobes, i.e. bacteria that can respire both in the presence and absence of oxygen. However, denitrifying bacteria are commonly found in conditions of little to no oxygen (oxygen concentration of less than 10%) where anaerobic respiration dominates. These conditions often occur in soils with a low supply of oxygen, such as flooded soils with water filled pore space, where bacteria utilise nitrate instead of oxygen for respiration.

Denitrifying bacteria are responsible for breaking apart N-containing elements, using the released electrons to provide energy for cell respiration and converting nitrate to N_2 in the process. Nitrate is the terminal electron acceptor in a chain of reduction reactions whereby nitrate (NO_{3^-}) is first reduced to nitrite (NO_{2^-}), which in turn is reduced to NO, then N_2O and finally to N_2 (Pan and others, 2022). Each transitional molecule is utilised by bacteria as a respiratory substrate to drive cell respiration, however the energy yield for each reaction steadily decreases with each step in the denitrification process. This is due to the ability of NO_{3^-} molecules to accept the most electrons, whilst the reduction of N_2O to N_2 requires the least electrons and thus has the lowest energy yield (Bradley and others, 2011).

Denitrification is a process that is ubiquitous in the Earth’s terrestrial and aquatic ecosystems, occurring in soils, freshwater and marine systems, aquifers, and it is used in wastewater treatment plants to remove N from wastewater. The process is pivotal in the N cycle as it completes the transition back to elemental N that is then available to be fixed by plants as organic N, thus restarting the cycle.

There are a number of factors which affect the process of denitrification and promote the conditions necessary for complete denitrification. For example, there needs to be a source of OM in the soil as it acts as an energy source for denitrifying bacteria; this often takes the form of carbon from fallen leaf litter. The land-use and consequent quantity of organic carbon available to denitrifying bacteria therefore affects the potential for long-term N retention in soils (Zhang and others, 2020). Additionally, the reaction depends upon enzyme activity meaning that a higher temperature and pH within the range of 8-8.6 is optimal (Bremner & Shaw, 1958). The moisture content of the soil is also important, as saturated soils are ideal for providing the anoxic conditions under which denitrification is most efficient (Groffman and others, 2002).

Denitrification and assimilation are the key processes or nitrogen removal, however physiochemical processes such as ammonia adsorption, sedimentation and volatilisation can also aid N removal. During adsorption, ionised ammonia binds loosely to substrates such as clay, detritus and inorganic sediments or soils. Humic substances present within the water aid chemisorption or fixation of ammonia within the clay lattice. Water chemistry conditions dictate whether ammonia is adsorbed to sediments, with desorption occurring when ammonia concentrations reduce. Sorbed ammonium oxidises to nitrate when the substrate is exposed to oxygen (Vymazal, 2007), with nitrate then able to be denitrified to remove N from the environment. Further factors which affect the rate of adsorption are the amount and characteristics of clay, OM and soil available, the alternative periods of submergence and drying of sediments, and the presence of vegetation (Lee and others, 2009; Wang and others, 2021).

The removal of particulate organic nitrogen from water is completed via sedimentation processes, where nitrogen bound to particulates settles out of water flows or adheres to plant stems. Volatilization is the process of transforming aqueous ammonia to gaseous ammonia, where the gaseous and hydroxyl forms of ammonium are in equilibrium. The main factor that affects the success of volatilisation within flooded soils and sediments is pH, with pH 9.3 or above showing best removal (Vymazal, 2007)

Table 5:3. Summary of conditions required for denitrification to occur.

Removal process	Summary of conditions	References
Optimal conditions for denitrification	Anaerobic conditions Source of OM in the soil (often fallen leaf litter) High temperature pH within the range (8 – 8.6) Saturated soils often provide the necessary anoxic conditions	Bremner & Shaw (1958) Groffman, and others (2002) Skiba, and others (1993) De Boer & Kowalchuk, (2001) Hayatsu, and others (2008)

5.5 Nitrogen and phosphorus removal by bacterial and plant uptake

Plants and bacteria assimilate N and P, which are key macronutrients used for biomass production. These processes temporarily lock up the nutrients, acting as a form of nutrient removal from the environment. In systems containing annual plants, nutrient removal through plant uptake is dependent on harvesting at the end of the growing season in order to prevent decomposition and the subsequent recycling of N and P in situ. For perennial plants, the longevity of removal by plant uptake is heavily dependent on the lifespan of the plants and how much biomass a plant sheds over time, e.g. from leaf fall or dying tree limbs (Johnston & Dawson, 2005). The scale of plant nutrient uptake is also affected by plant type and uptake is active only during the growing season when plants accumulate biomass. Senescence of vegetation and subsequent decomposition can re-release sequestered N back to the environment, however some N can remain trapped within soils for long periods of time (Zhang and others, 2020). This study also suggests that the soil texture will influence N retention, with finer soils retaining less organic N from vegetation inputs. The permanence of N uptake by vegetation can also be lengthened if biomass is harvested and removed (Johnston & Dawson, 2005).

The key difference between N and P removal by bacterial and plant uptake in terrestrial and aquatic ecosystems is the lifespan of plants in each environment. Terrestrial environments can support the growth of larger, woodier vegetation that has a longer lifespan and takes more time to degrade, providing a longer-term solution to nutrient uptake (Haycock, 1997). Regardless of the environment, perennial vegetation is preferable over annual plants as the processes by which nutrients are assimilated are guaranteed more time to occur and remobilisation via decomposition is a less imminent problem. Aquatic vegetation typically will have a shorter life span and is characteristically less woody than terrestrial plants. As such, aquatic vegetation will degrade more quickly in conditions of periodic saturation, whereby the oxygen and moisture content are optimised for decomposition (Yoon and others, 2014). Thus, nutrients are more readily re-mobilised in aquatic environments.

Table 5:4. Summary of conditions required for bacterial and plant uptake of N and P to occur.

Removal process	Summary of conditions	References
Optimal conditions for plant uptake of nutrients	• Annual harvesting and removal of vegetative biomass – more important for P than N • Perennial, as opposed to annual, plants • Large, woody vegetation are preferable	• Johnston & Dawson (2005) • Haycock and Pinay (1993) • Mainstone and Parr (2002)

6. Nutrient export from semi-natural habitats

6.1 Overview of the greenspace export coefficient used in nutrient budget calculations

N and P export coefficients for greenspace and other semi-natural land uses are provided as part of the generic methodology for calculating nutrient budgets for new developments (Ricardo, 2021). These export coefficients have subsequently been used in the calculation of the nutrient mitigation that can be delivered through agricultural land conversion schemes. This section provides an overview of the approach taken to setting these greenspace export coefficient values for N and P, in order to provide context for the following sections that provide a review of other potential sources of information for setting N and P export coefficients from semi-natural habitats. This section also provides useful context on the rationale behind choosing the greenspace export coefficient which is likely to be used to help calculate post-conversion nutrient exports.

In the context of nutrient budget calculations, greenspaces refer to semi-natural outdoor spaces provided for recreational use where fertilisers will not be applied, and dog waste is managed. This does not include green infrastructure within the built urban environment, such as sports fields, gardens, or grass verges, as these are included in the updated urban N and P export values. Values for these coefficients were calculated based on collating data based in studies by Hobbie and others (2017), Johnes (1996), Natural England (2020) and Groffman and others (2009).

The coefficient export value for P in greenspace was originally calculated using a combination of data on P input (kg/P/ha/year), P export (kg/P/ha/year), background P export and a P retention rate in soils. A 90% retention rate was selected based on the assumption that the main source will be pet wastes, which reduced the export value from 1.21 to 0.12 (Hobbie and others, 2017). A background export value from natural land uses as applied in Johnes (1996) was then added to this value to result in a final value of 0.14. An issue of double counting of P export from greenspaces situated with the urban fabric was acknowledged (where N and P inputs from pet waste are captured in estimates of N and P export for residential land use), so to avoid overly high export coefficient values, a natural land P export value of 0.02 kg/P/ha was chosen from Johnes (1996).

The value of 0.02 has been cited by several academic publications, however a review of these sources reveals little explanation behind this value. Many publications citing Johnes (1996) have also neglected to provide explanations of their rationale behind the selected value of 0.02. It is important to acknowledge the uncertainty associated with this P export coefficient value, which thus warrants further research to identify if other values have been proposed, especially for different types of natural or semi-natural land uses.

Greenspace N export coefficient values used in the nutrient budget methodology were derived using data for N input (kg/N/ha/year) and retention rates by greenspaces. Atmospheric N inputs to greenspaces were determined using the national average N deposition rate of 16 kg/N/ha/year, which aligns with N deposition rates used in Farmscoper. Inputs of N through plant fixation were estimated at 14 kg N/ha/year based on established rates of N fixation in in vegetation typical of greenspace (Hobbie and others, 2017). As with P, N inputs from pet waste were removed from this calculation to avoid double counting (as inputs from pet waste are captured in estimates of N export for agricultural land use). The total input (30 kg/N/ha/year) was then reduced by a soil N retention rate of 90%, resulting in a final greenspace N export coefficient value of 3 kg/N/ha/year[4]. The 90% retention was applied as it was assumed to be representative of typical N loss rates due to N cycling and plant uptake.

Table 6:1. Summary of key values used to calculate the greenspace N and P export coefficients

Inputs	Data summary	References
Values used to calculate P export coefficient value	P retention rate: 90% Pet waste inputs: 1.21 kg/P/ha/year Natural land export: 0.02 kg/ha/P/year **Result**: 0.14 kg/P/ha/year	• Ricardo (2021) • Hobbie and others (2017) • Johnes (1996)
Values used to calculate N export coefficient value	N retention rate: 90% National average N deposition: 16 kg/N/ha/year N fixation inputs: 14 kg/N/ha/year **Result**: 3 kg/P/ha/year	• Ricardo (2021) • Hobbie and others (2017)

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[4] Although the evidence base for this value is not large, the range of values (~1 to 14) suggests 3 kg/N/ha to be a reasonable average. This method is based on various assumptions and local variability in N deposition is likely to drive local variations in coefficients.

6.2 Assessment of variation in nutrient export from semi-natural habitats

This section provides the findings from a review of the variation in N and P export coefficients from semi-natural habitats which are documented in the literature. Literature was sought on semi-natural habitat types taken from the UK Centre for Ecology and Hydrology Land Cover Map (Centre for Ecology and Hydrology, 2017), which are defined in Appendix 2. The literature search focused on the following semi-natural habitat types: broadleaved woodland, coniferous woodland, neutral grassland, calcareous grassland, acid grassland, saltmarsh, heather and heather grassland (together encompassing the dwarf shrub heath broad habitat type). These semi-natural habitat types were chosen as it is possible for previously agricultural land to be restored to these habitats. Other types, such as littoral sediment, bogs, and fens, were rejected from the initial list as it is unlikely that agricultural land will be converted to such habitats.

6.2.1 Nitrogen

N inputs to semi-natural habitats are primarily from atmospheric N deposition, and N fixation by plants. If an area of semi-natural habitat is used for recreation, pet waste inputs may also be significant, however for the purposes of this review pet waste inputs are not considered. Omitting pet waste is aligned to consultation with NE where it was agreed that the higher residential urban land N export values applied in the generic nutrient budget approach (Ricardo, 2021) can account for pet waste due to new developments. There is also a paucity of research on the contribution of pet waste to N loading in semi-natural habitats. Similarly, there is lack of research on the scale of N fixation inputs to the semi-natural habitats assessed in this review. Most studies focus on experimental manipulations to assess N fixation rates of specific types of vegetation rather than the fixation rates typical of semi-natural plant communities. An N fixation rate of 14 kg N/ha/year was proposed by NE in the Solent nutrient neutrality advice note (Natural England, 2020) and taken from Hobbie and others (2017). No further evidence to dispute this value has been found.

N deposition to semi-natural habitats occurs through either dry deposition of gaseous forms of N or wet deposition of gaseous N that has dissolved into precipitation. Atmospheric deposition of N to terrestrial environments can cause an increase in N leaching and export (Matson and others, 2002), and atmospheric deposition is known to be a dominant input of N into semi-natural habitats (Power and others, 2001). This is reflected by most studies of N dynamics in semi-natural habitats, which tend to provide some estimate of N inputs from atmospheric deposition but rarely quantify N fixation. It was also found that various studies reference a decline in atmospheric N emissions since at least the year 2000 (e.g. Power and others, 2006; Monteith and others, 2016). As such, literature searches were limited to studies from the past 10 years in order to assess whether the national average N deposition value of 16 kg N/ha/yr used to calculate greenspace N export (see above) may see departures for certain habitat types. A recent study by Payne and others (2020) provided the most comprehensive review of N deposition rates, compiling 36 datasets on N deposition values for different habitats in the UK from studies largely completed post-2010. These data showed that a single habitat type can show considerable variation. Heathlands, grasslands and moorlands all showed variability in N deposition from lower values of the order of 5 kg N/ha/yr to upper values of the order of 30 kg N/ha/yr. This variability is likely due to a combination of site-specific conditions such as the concentrations of N in throughfall, soil pH, temperature and the C:N ratio of soils, whereby througfall N flux is evidenced to be the strongest indicator (Dise and others, 2009). This shows the potential variability in N deposition that can occur for a single habitat type. If a single N export value for semi-natural habitats is to be used for mitigation schemes that convert land from agricultural uses then this variability lends further support to the use of the national average 16 kg N/ha/yr in the derivation of a greenspace export coefficient. However, if bespoke values are used for each mitigation scheme then local variability in atmospheric deposition should be accounted for in order to determine a more specific local export coefficient.

The N inputs to semi-natural habitats are removed by two main processes: denitrification (see section 5.4) and bacterial and plant uptake (see section 5.5). All semi-natural habitats facilitate these removal processes, however there is likely to be variation in the dominance of each process dependent on environmental conditions in a given semi-natural habitat. For example, density and type of vegetation is likely to alter the rate at which N is taken up and stored in plants, with woodland and heathland likely to see greater N storage in biomass than in grassland. Environmental conditions such as soil drainage and pH will have an impact on the denitrification potential. A lack of studies were found quantifying the impact of these N removal processes on a kg N/ha/yr basis and thus it has not been possible to provide additional clarity on the impact of these processes on N export coefficients for different semi-natural habitats.

Denitrification and vegetation uptake are key drivers of the aforementioned 90% soil N retention rate applied to the calculation of the greenspace N export (see section 5.1). This 90% soil retention rate is taken from an American study by Groffman and others (2009) on nitrate leaching in urban forests and grasslands. This study found that N retention in their experimental plots ranged from 60% to 100%, being lowest in wet years. They then cite a range of studies that have shown that managed grasslands often achieve N retention rates > 90%. A review of additional literature found few other studies that provided percentage N retention rates for soils across any semi-natural habitat types, though some studies did report similar retention rates. One study measured rates in an upland peatland environment (89-96%; Verry & Timmons, 1992). Another study showed the retention efficiency to range from 85-99% within pine and hardwood forests (Aber and others, 1998). There is consequently some uncertainty associated with the 90% soil retention rate estimate, though it is line with the literature and there are limited alternatives.

A limited number of studies have been found that propose N export coefficients for certain semi-natural land uses. Johnes (1996) suggests that woodland and grassland (named rough grazing but described as unfertlised grassland) both have an N export of 13 kg N/ha/yr, with this estimate taken from studies dating to the 1970s and 1980s. A more recent study on the impact of woodland on reducing nitrate leaching to groundwater suggests the following N export rates for different semi-natural land uses: woodland – 8 kg N/ha/yr, grassland – 5 kg N/ha/yr, all other non-agricultural land – 5 kg N/ha/yr (Zhang & Hiscock, 2011). The values in this study were in turn taken from previous literature reviews dating from before 2010 with little explanation of how they were actually derived. Research from New England USA, suggested an average N export of 1.35 kg N/ha/yr over a two-year study (Gold and others, 1990), though this study is both old and a less relevant geography. A Danish study looking at the affect of conversion from agricultural land to forest reported higher N export for previously arable land that had been converted to forest (15.9 kg N/ha/yr ± 12.9 SD) than for histrocially forested land (4.5 kg N/ha/yr ± 9.1 SD; Gundersen, 2009). MacDonald and others, (2002) report results from a large database of studies of N export from European forests. Most of the study sites in this database were coniferous (114), with only 28 results from broadleaved forests. The mean N export coefficient for these forests was 5.8 kg N/ha/yr, however this mean is likely being skewed upwards by a small number of high export coefficients as 64% of sites recorded export coeffieicnts < 5 kg N/ha/yr.

Based on the above analysis, there is clearly a general lack of substantive evidence that can be used to set an N export rate from specific semi-natural land uses with confidence. Whislt there are many papers that discuss this subject, few of the studies provide export coefficients in kg N/ha/yr[5] and many of those that have are >20 yeas old (Gold and others, 1990; MacDonald and others, 2002). These are likely outdated given the decrease in N emissions and thus N deposition that has been occuring over the past 20 years or more. As such, an approach to setting semi-natural N export values using estimates of N deposition, N fixation and soil retention rates taken from the literature is still deemed the best approach to setting a background N export rate from semi-natural habitats. It is recognised that there are likely to be differences between the actual background N export rates from differrent habitats but it has not been possible to determine them with confidence through this review. More accurate N export coefficients may be acheivable if local variabiltiy in N deposition is taken into account.

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[5] Although there is a large evidence base for the flux of N in semi-natural habitats, few of these studies provide export coefficients in the relevant units which causes problems when comparing values.

Table 6:2. Key conclusions regarding N export from semi-natural land use

N input	Data summary	References
Sources of N to semi-natural habitats	Dry deposition (gasses) Wet deposition (precipitation) Pet waste (omitted as considered in residential calculations) Background export	Matson and others (2002) Power and others (2001)
Reasons for variation	Likely variation with different vegetation, though evidence for this is not available National variation in atmospheric deposition Canopy interception	Monteith and others (2016) Dise, and others (2009)
Conclusion	Too little evidence to ascertain potential reasons for export variations between habitats Differences are likely, yet unknown Best approach remains using N deposition values with fixation rate and soil retention efficiency	

6.2.2 Phosphorus

Semi-natural habitats do not tend to have significant inputs of P. The main source of P to semi-natural habitats is animal waste. As is described above for N (Section 6.2.1), pet waste P inputs to semi-natural are not considered due to the high P export coefficients determined for urban land uses in nutrient budget calculations (Ricardo, 2021). A literature search for the impact of wild animal excretions on P loading to semi-natural habitats did not yield any results.

As estimates of the P inputs to semi-natural habitats have not been found, it was not possible to take the same approach as applied to N and reduce the P input by a soil retention rate. In the generic nutrient budget approach methodology, a value of 0.02 kg P/ha/yr is used as the export coefficient for semi-natural land uses (Ricardo, 2021). This value originated in a study by Johnes (1996) and has subsequently been used in other studies that required a P export coefficient for semi-natural land uses (e.g. Hanrahan, and others 2001). Further assessment of studies from outside of the UK has found P export values for woodlands that range from 0.15 - 0.36 kg P/ha/yr and P export values for grasslands, bogs, and dwarf shrub heathland in the range of 0.07 - 0.13 kg P/ha/yr (Institute of Freshwater Ecology, 1996; Smith and others, 2005). These studies did not provide a clear rationale for how these values were derived and thus the reason behind the variation is unclear.

Although higher export values for some studies outside of the UK have been found, there is currently not enough evidence to suggest that the 0.02 kg P/ha/yr should be altered. As with N (see Section 6.2.1), it is recognised that a single P export value for semi-natural habitats will mask natural variability between habitat types but there is currently insufficient evidence to propose habitat-specific P export rates. Further research to better understand P export from semi-natural habitats would be beneficial to determine more accurate baseline P export coefficients for land post-conversion from agriculture.

6.2.2.1 Legacy phosphorus

Woodland planting and rewilding schemes on agricultural land reduce P loading through reduction in the use of phosphate-rich fertilisers and production of animal waste. Soil erosion and associated P mobilisation is also likely to decrease with time as soil is stabilised by more continuous vegetation cover. However, unpublished research from the RePhokus[6] research project has raised the potential of large lag times for P loss to revert to background levels. This is due to the persistence of P stored within soils that can continue to leach from soils that have received high P inputs from agriculture. Some studies on the longevity of this legacy P have recorded timescales for P export to return to background levels of 23-44 years in New Zealand, over 17 years in the US, and 7-15 years in Irish soils (Cassidy and others, 2017). Residence and recycling times within these P legacy stores depends on soil type, soil P concentrations and management and thus are highly variable between different locations. Consequently, there remains many uncertainties related to P legacy in terms of the level of P reduction which abandoned agricultural land can achieve in the short- to medium-term. It is therefore important that calculations of P reduction from abandoned agricultural land account for this lag and adjust for longer timescales; assuming P levels will remain above background for up to 20 years unless monitoring reveals otherwise, or that the land is managed in a way to promote P uptake and reduce soil erosion (e.g., NbS practices woodland planting or field drain blocking). In addition to these practices to mitigate and increase the uptake of legacy P in abandoned soils, a greater emphasis is also needed on more efficient use of P stored in existing agricultural land as to minimise future legacy P loads (Jarvie and others, 2013).

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[6] See: Resilience Phosphorus UK – Re-focusing phosphorus use in the UK food system (lancs.ac.uk), accessed on: 08/04/2022

Utilizing agricultural land conversion sites to grow crops which remove legacy phosphorus from surface soils, without the addition of P from fertilizers or manure, could be recommended prior to restoration to account for the lag time of land conversion schemes. Eghball and others (2003) found that over four years of corn production the surface soil extractable P reduced by 35.47%. However, there is not enough data or literature available to suggest a reasonable timeframe in which cropping should be conducted prior to conversion. Removal of P is limited by the need for adequate N levels, the type of crop grown as well as the majority of P removal being from surface soils (0-15cm). Furthermore, the rate of P removal was higher at higher P soil concentration with the rate slowing as soil P concentration decreased. However, cropping of agricultural land in this way prior to woodland planting or rewilding is likely to provide some reduction in the lag time for P to reach background levels.

Table 6:3. Key conclusions regarding P export from semi-natural land use

Key consideration	Data summary	References
Sources of P to semi-natural habitats	• Pet waste (omitted as considered in residential calculations) • Background export	• Ricardo (2021)
Reasons for variation	• No rationale behind values ascertained from literature, therefore reason behind variation is unclear • Issues regarding P legacy	• Johnes (1996) • Hanrahan and others (2001) • Cassidy and others (2017)
Conclusion	• Too little evidence to ascertain potential reasons for export variations between habitats • Differences are likely, yet unknown • Insufficient evidence has been found to suggest a change from 0.02 kg P/ha/year • Suggest cropping of agricultural land prior to conversion to account for lag in legacy phosphorus removal	• Eghball and others (2003)

7. Land use change to promote natural nutrient removal processes

The solutions evaluated in this report are NbS that involve changing land use and land management to promote natural processes that remove nutrients. It is also noted that the NbS reviewed below will also provide additional benefits beyond nutrient mitigation, such as carbon sequestration, reduced flood risks, increased biodiversity and increased amenity value. Each of the chosen NbS are reviewed in the sections below, with each section providing an overview of the processes of N and P removal a solution promotes, the factors that affect the efficiency of N and P removal, an estimate of N and P removal efficiency where possible, and a summary of the evidence for each solution. Where relevant, the links between each of the following NbS options to overall restoration approaches are outlined in Section 4.

7.1 Riparian buffers

Buffer strips can either be located within a field, at field margins or along the riparian corridor. From a nutrient removal perspective, the overall chemical and physical removal processes active in these systems remain similar regardless of their location, though the overall effectiveness is dependent upon a range of local environmental conditions and their spatial scale. Most of the literature on nutrient pollution control focusses on riparian buffers as the direct effect on local waterbodies is easier to monitor. Literature concerning field margin buffer strips is more often interested in the nutrient removal effect on nearby habitats with heightened susceptibility to nutrient pollution, such as local nature reserves (De Cauwer and others, 2006).

7.1.1 Processes of nitrogen and phosphorus removal

Nitrogen enters buffer strips either via surface run-off pathways from adjacent land-use or subsurface flows. The relative importance of these sources is dependent upon the nutrient source and the local environmental conditions, such as soil type and geology (Muscutt and others, 1993). In the instance of surface flows, deposition of sediment bound P is the first and most dominant removal process. Vegetation increases the hydraulic roughness of a buffer relative to agricultural fields, helping promote the deposition of sediment-bound P whilst also providing a constant source of OM to promote denitrification. Coarse sediment is generally trapped as overland flow enters a buffer, whilst finer sediment requires longer distances and significantly decreased velocities to come out of suspension (Stutter and others (2020). For dissolved P, greater buffer widths are required for the P to come out of solution and be deposited (Haycock, 1997).

As a result of the hydraulic roughness and surface heterogeneity characteristic of riparian buffer strips, infiltration of surface water is likely to occur. Due to the presence of both subsurface flows and the infiltration of surface water, the majority of nutrient removal processes occur within the soil matrix (Valkama and others, 2019). For these processes to be effective, water must pass through the rhizosphere, whereby conditions are most favourable for denitrification, for example. As most agricultural N pollution takes the form of nitrate, the main subsurface mechanism of N removal is denitrification. When subsurface flows enter the buffer strip at the correct depth, as opposed to bypassing the root systems via deeper channels, the conditions are favourable due to the high soil moisture causing anoxia, and high carbon content, sourced from surrounding OM (see Section 5.4). Denitrification is typically concentrated at the upper edge of the buffer as this is where nitrate is most abundant and denitrifying conditions are most favourable (Haycock & Pinay, 1993). These site-specific conditions should be considered in the design process of a mitigation scheme, with seasonally consistent N removal processes occurring where the conditions are right.

Sorption to sediments and soils is the primary subsurface removal process for P, also occurring to the greatest extent at the field-side edge of a riparian buffer. This is due to the system seeking equilibrium between the soil EPCo and water P content (see Section 5.3), i.e. the greatest load of P within the buffer tends to be from agricultural sources, therefore promoting faster uptake as water enters the buffer from surrounding agricultural land (Vought and others, 1994).

Nutrient removal by plant assimilation is active for both N and P, although research suggests it is less important compared to denitrification and soil sorption (Brinson and others, 1984). This is in part due to nutrient retention in vegetative biomass being temporary, with N and P in vegetation remobilised upon senescence and decomposition. As such, the relative importance of plant uptake as a solution, increases with biomass harvesting. However, even with a maintenance scheme in place, plant uptake immobilises a relatively small amount nutrient pollution (Reddy and others, 1998). This is justified by most removal mechanisms occurring in the soils. As such, biological assimilation functions more to prevent soil P saturation whilst fallen leaf litter acts as a source of OM to denitrifying bacteria. Riparian planting also has considerable additional benefits through the reduction in overland flow velocities that prevent soil erosion and also stabilise riverbanks, resulting in less bank erosion and the associated input of sediment-bound nutrients to rivers. More complex root structures caused by larger plants also increase hydraulic residence times of water the soils of buffers, increasing the time chemical nutrient removal processes have to occur (Johnston & Dawson, 2005).

The processes detailed above work in tandem to mitigate nutrient loading in buffers, though no study has evaluated the comparative effectiveness or significance of each mechanism in one system (Haycock, 1997). This makes comparisons of removal rates difficult, though it has been suggested that assimilation by vegetation accounts for a small proportion of nutrient removal (Brinson and others, 1984).

7.1.2 Factors that affect nitrogen and phosphorus removal efficiency

Vegetation in buffer strips contributes OM and carbon to the soil, enhancing the denitrification and P sorption capacities of the system, making vegetation a key factor to consider in implementing riparian buffers for nutrient removal. Width and the type of vegetation planted in a buffer strip may also have a large impact on nutrient removal by sediment deposition. Vought and others (1994) found that surface runoff travelled 16 m into a grassy buffer strip, whilst only travelling 4 m in a wooded buffer strip. This suggests that wooded buffers can be narrower whilst still promoting sediment deposition and infiltration. Valkama and others (2019) support this conclusion, reporting that although wooded buffers don't seem to enhance the rates of N removal in surface flows, they are 10-15% more effective at removing N via subsurface processes. Given that the majority of N removal occurs below the surface, the lower nutrient removal from surface flows in wooded buffers is less important. As such, the benefits of improved groundwater N removal outweigh the potential for slowed surface reactions. The benefits of wooded buffers for nutrient removal have also been reported in other studies (Zhang, and others 2010; Vought and others, 1994; Christen & Dalgaard, 2013).

Vegetation type is another key biological factor influencing nutrient retention. Forested riparian buffers are more effective as a source of large wood in stream which can increase channel complexity and hence further increase nutrient uptake. Woodlands also serve as windbreaks, reducing wind erosion of agricultural soils which can provide an additional source of nutrients to aquatic systems. And, as bank erosion causes 14% of sediment pollution to UK rivers, with a high associated nutrient load (Environment Agency, 2019), planting types of vegetation on buffer strips that will maximise bank stability is an important factor to improve their efficacy. The rooting depth of vegetation also has an effect on denitrification rates, as OM released through root exudates is most beneficial to denitrifying bacteria when released at or close to the depth of the water table; this prevents carbon from limiting the speed of nutrient cycling. In instances where carbon isn't limiting, denitrification is limited by the rate at which nitrate diffuses from active regions of nitrification (aerobic zones) to active regions of denitrification (anaerobic zones) (Reddy and others, 1976). The most important environment for nitrogen cycling is therefore the interface between these regions, where the water table meets unsaturated sediments (Haycock, 1997). In the context of implementing mitigation measures, this is important to understand as nitrate is not the only input of nitrogen into riparian buffer strips. As denitrification occurs primarily at the interface between saturated and unsaturated soils in the rooting zone of riparian vegetation (Haycock, 1997), the ideal soil hydrology for riparian buffers will balance the need for soils to maintain an unsaturated layer that can promote infiltration of surface water run-off but with a relatively high-water table needed to promote denitrification. The balance of these conditions should be considered relative to the sources of water entering a buffer in order to optimise removal of N and/or P from surface and/or sub-surface flow pathways.

Consideration should also be given to the quantity of vegetation, as well as the variety of species present. It is important to promote the growth of an array of native vegetation from both a biodiversity and nutrient removal perspective. Richards and others (2010) explain nutrient assimilation rates to be greater in mixed species stands when compared to monocultures. More nutrients are held in aboveground biomass due to changes in plant physiology when grown in biodiverse environments. These changes allow tree species to uptake more nutrients due to the development of greater nutrient-use efficiencies, resulting in less nutrients available for leaching in the soil (Richards and others, 2010). These benefits are most evident in younger buffer strips, with intermediate aged (15 years) trees retaining more nutrients than older stands (Hill, 2019; Valkama and others, 2019).

Buffer width has been found to be one of the most important influences on nutrient retention. As well as allowing for sediment deposition and infiltration to occur, wider buffers also allow for greater hydraulic residence times. For P removal, a wider buffer provides more soil for P to sorb to allows more time for P penetration into soil particles to occur, completing the process of adsorption. There is a lack of scientific confidence regarding the optimal width, though it has been suggested that there is little to no benefit in having buffers wider than 20-25 m (Vought and others, 1994). Six metres is suggested to be the likely minimum width in the context of nutrient retention (Stutter and others, 2020). This study also suggested that buffer width accounts for less than a third of sediment trapping efficiency, with local environmental factors such as soil type, slope, and rainfall intensity having notable influences.

Soil type will influence the infiltration capacity of soils, being higher for sandy soils and lower for clay soils. In this context, the infiltration capacity mainly concerns the infiltration of nutrient rich surface flows from adjacent land-uses such as agriculture. As the majority of nutrient removal processes occur in subsoils, it is essential that riparian buffers promote infiltration of overland flows. Hill and others (2019) evidence the importance of balancing the infiltration capacity of soils with their nutrient removal potential, reporting that sand and gravel buffers require 30-60 m to achieve 90% removal of nitrate, whilst fine grained sediments require 10-20m to achieve the same result. For P removal, soil type has also been suggested as a key factor in buffer strips, with P binding more readily to clayey soils (Stutter and others, 2020). It should be noted, however, that soil P saturation can occur and result in buffers switching from sinks to sources of P. A study by Young and others (2018) reported riparian buffer effectiveness to likely decrease over time as soil adsorption sites are taken and overland flow P concentrations decrease. This is worth considering as a long-term factor affecting the efficacy of riparian buffers as mitigation solutions as there is potential for concentrations in run-off to decrease in response to changes in agricultural management. Despite this, there is a lack of understanding regarding the likelihood and timescales for this switch to happen as few studies carry out long-term monitoring of buffers, though it has been suggested that harvesting vegetation and removing the P locked up in biomass can be used to increase the longevity with which buffers can continue to remove P (Stutter and others, 2020).

Vegetation management can also help to reduce the risk of soil erosion within a buffer strip, which can in turn increase the effectiveness of the buffer for nutrient retention. Buffers with closed canopies limit light reaching understory vegetation, which in turn can increase the exposure of soil to erosion. The gradient of a buffer is also likely to impact both the potential for soil erosion and the infiltration capacity of the soil, with higher gradients likely to limit infiltration and increase soil erosion. However, studies have suggested that percentage nutrient removal efficiencies may not show a decreasing trend with increasing slope (e.g. Darch and others, 2015).

7.1.3 Estimates of nitrogen and phosphorus removal efficiency

The precautionary maximum estimates of Nitrate and TP removal efficiencies for riparian buffers have been derived by Entrade and ARUP and set out in the Interim Nutrient Reduction standard (ARUP and Entrade, 2022). Nitrate and TP have been chosen as the nutrient types to be examined to remain consistent with Farmscoper which will likely be used to calculate the baseline loads. As nitrate is a portion of Total Nitrogen the reductions will also be precautionary. EnTrade's assessment of nutrient retention in buffer strips suggests a 10m minimum width, with nutrient retention increasing when the buffer width increases (See Table 7:1)[7]. The overall nutrient reduction therefore depends on the width chosen for the buffer strip. See the Nutrient Reduction Standard for more information. These figures were derived based on data on nutrient reduction against buffer width and the regression equations (For P $y=39.5x0.24$and for N $y=1.30x + 43.2$) presented by Schoumans and others (2011) which uses data from Collins and others (2009) on riparian buffers. The reduction calculated for the first 2m (using the regression equations) was deducted for each width, to take account of the fact that a 1m (and is some cases up to 2m) buffer is already required through existing agricultural regulations. Although the regression equations are not particularly precautionary the deduction of the first 2m reduction which will be greater than is currently required in many cases (i.e. 1m) ensures that the final reduction efficacy values are suitably precautionary. **Part 2** (The Framework) provides details on applying these figures.

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[7] Table 7:1 represents EnTrade's efficacy coefficients for buffer strips, using the best available information as of 13/01/2024

Table 7:1. Efficacy coefficients of riparian buffer strips, dependent upon their width

Additional interceptor width (meters)	TP reduction efficacy (leading 2m impact deducted)	Nitrate reduction efficacy (leading 2m impact deducted)
10+	0.22	0.10
12+	0.25	0.13
15+	0.29	0.17
18+	0.32	0.21
20+	0.34	0.23
24+	0.38	0.29
25+	0.39	0.30
30+	0.43	0.36

7.1.4 Summary of evidence

Denitrification and P sorption to sediments and soils are the primary mechanisms driving nutrient retention in buffer strips. To promote these processes, design, and management of buffer strips to support certain conditions are recommended. These include planting vegetation to improve the OM content of the soil, aiming to increase hydraulic residence times, having a suitably wide buffer, harvesting and removing vegetation, and siting buffers in areas with high influent nutrient loads. The proposed riparian buffer strip width of 10m (Nutrient Reduction Standard) is a precautionary estimate of the minimum width for nutrient credits, however the amount of nutrient reduction is dependent on multiple factors, including the width of the riparian buffer. See **Part 2** (The Framework) for further information. The precautionary removal efficiency estimates should be regularly reassessed as monitoring data from riparian buffer strip mitigation schemes becomes available.

7.2 River channel re-naturalisation

River channel re-naturalisation seeks to reinstate natural processes to anthropogenically modified river channels through the reinstatement of natural channel forms and habitats. There are many methods of river channel re-naturalisation, such as channel reconfiguration, marginal vegetation planting, bank stabilisation and re-meandering among others. Not all approaches will be applicable to achieving nutrient neutrality and in the context of nutrient removal, river channel re-naturalisation primarily refers to floodplain reconnection, aiming to increase lateral connectivity by reconnecting floodplains, or alternatively connecting rivers to online wetlands, disconnected side channels and oxbow lakes. Encouraging the rivers to return to a more natural, heterogeneous state supports natural processes that have the ability to reduce N and P pollution. The following sections describe the processes that drive nutrient reductions in naturally functioning rivers and provides an assessment of whether a percentage efficiency for N and P removal can be derived from the literature on river channel re-naturalisation. It should also be noted that river channel re-naturalisation and buffer strips (see Section 7.1) are complementary measures and river channel re-naturalisation could help to increase the success of a riparian buffer strip if bank reprofiling can help to facilitate connectivity between groundwater and the rhizosphere in riparian buffers.

7.2.1 Processes of nitrogen and phosphorus removal

Denitrification and P sorption to sediments are some of the principal processes driving nutrient removal from river systems (see Sections 5.3 and 5.4). In natural channels, both processes are highly influenced by the contact time of water with bed sediments. Natural channel complexity increases flow turbulence, resulting in greater exchange of water with the hyporheic zone. This exchange allows denitrification to occur via the oxidation of OM simultaneous with nitrate reduction, forming gaseous oxides of nitrogen that remove N from the system (Ensign & Doyle, 2005). These processes are also promoted via the stream flow’s extended contact time with floodplain sediments as a result of increased lateral connectivity, causing nutrient storage away from the channel. Denitrification can also be facilitated by increased surface roughness and associated reductions in flow velocity caused by the geomorphic and habitat heterogeneity typical of natural river channels, which in turn promotes longer contact times with sediments and more time for denitrification to occur.

Sorption of dissolved P to sediments will also increase with increased contact of river flow with hyporheic sediments. The initial sorption of P to sediments happens quickly and its rate is relatively unaffected by residence times (Johnston & Dawson, 2005). However, P that is sorbed to sediment can be readily re-mobilised back into a stream and thus longer hyporheic residence times are needed for dissolved P to complete penetration into sediment particles and lock P within sediments for a longer period of time (Johnston & Dawson, 2005). Removal of particulate P by sedimentation, affected by the time and spatial extent of streamflow’s contact with the riverbed (See section 5.3), is a key determining factor of both the rates and longevity of nutrient retention (Pinay and others 2002). The process is also dependent upon the EPCo (See Section 5.3), precipitating removal of P from the water column if the P concentration of overlying water is greater than the EPCo. In the reversed scenario whereby the EPCo is greater, desorption occurs (Lucci and others, 2010). Nutrient uptake by vegetation (see Section 5.5) will also be more prevalent in restored river channels via the encouragement of natural vegetation due to their higher in-channel and marginal vegetation densities. However, most vegetation in rivers is relatively short-lived and the nutrients stored in plant biomass are likely to remobilised when plants die and decompose growth. However, increased lateral connectivity and the consequent re-establishment of more permanent floodplain and wetland vegetation can result in longer-term vegetative nutrient uptake, showing the benefit of nutrient storage away from the hyporheic zone.

Restoration schemes that increase vegetation abundance will also help to promote the hydrodynamic processes that increase transient storage, reduce velocities, and increase the abundance of organic debris within the channel. These secondary processes help to increase rates of denitrification and P sorption and deposition, so whilst plant uptake does not contribute significantly to N and P removal, vegetation can play a large role in other nutrient removal processes through increasing channel heterogeneity.

Studies of woody debris suggest that reduced P concentrations downstream of debris dams occurs due to adsorption of P to woody debris in the channel, particularly in areas of high P concentrations (Harper and others, 1999). However, debris dams are often only temporary and can be washed out by high flow events. Woody material will also eventually degrade if left in situ. Both of these processes are likely to result in woody debris providing only temporary store of P through adsorption. However, river channel naturalisation schemes that result in an increase in woody debris within river channels are also likely to aid in the restoration of lateral floodplain connectivity by slowing flow and increasing the probability of out of bank flows. Increased floodplain connectivity can provide a more permanent reduction in P in river channels through P deposition on floodplains.

It should be noted that the use of logjams are discussed as a separate NbS in section 7.4 as in the context of this study, logjams are considered to be a type of woody debris introduction to river channels that will cause a permanent change to channel form and nutrient removal through a slightly different set of processes.

7.2.2 Factors that affect nitrogen and phosphorus removal efficiency

Based on the processes that remove nutrients in natural or restored rivers, the key overall factor for re-naturalisation schemes to successfully reduce nutrient pollution is the reinstatement of habitat and geomorphic diversity. Restoration techniques that focus on maximising heterogeneity of channel forms are likely to increase the connectivity between benthic and riparian sediments and maximise the nutrient removal processes active within rivers (Pinay and others, 2002).

Geomorphic factors are also essential to the success of river channel re-naturalisation schemes to attenuate nutrient pollution. Headwater streams typically retain more N than larger rivers due to the hydrological connectivity between river-bed soils and groundwater (Pinay and others, 2002). These conditions promote denitrification. The increased contact between hyporheic and riparian stream interfaces resulting from reduced discharge in smaller streams also encourage nutrient cycling. The gradient of a river also has implications for N and P retention due to the effect of gradient has upon stream velocities (Filoso & Palmer, 2011). Lowland rivers are typical of having lower gradients; there is therefore potential for successful nutrient mitigation in both upland and lowland streams. Awareness of these considerations prior to implementation is advised to designate a reach suitable for restoration.

The initial N and P concentrations prior to restoration in a given reach are also important in optimising the success of a river restoration scheme for nutrient removal (Bernhardt & Palmer, 2011). Harper and others, (1999) suggest P removal through river restoration will function best when P concentrations are above 300 µg/l, though this will vary depending on the EPCo of stream sediments. P adsorption to sediments is likely to still occur under low concentrations, albeit at a reduced rate as the chemical process constantly seeks equilibrium between the concentration in the overlying water and the EPCo (See Section 5.3). Furthermore, if the dissolved P in water drops below that of the EPCo of benthic sediments, the sediments can act as a source of P through desorption until a new equilibrium is reached (Pant & Reddy, 2001).

River channel naturalisation schemes will also have the greatest benefit for nutrient removal if the main sources of nutrient pollution enter the river upstream of the restored reach, rather than at some point along the restored reach. This ensures maximum concentrations to support the various processes that remove N and P, as well as providing the nutrients with the longest period of time possible to be immobilised/removed. Siting river channel naturalisation schemes downstream of areas with known high nutrient pollution sources is therefore essential to achieving nutrient reduction opportunities related to both N and P.

Soil type inherently affects P sorption capacity as certain soils have significantly more sorption sites available for nutrient retention than others (Section 5.3). This cannot be adjusted to suit restoration schemes; however, awareness can aid the process of producing P reduction estimates. Further affecting nutrient retention in the hyporheic zone, there is potential for carbon limitation in sediments to prevent denitrification (Krause and others, 2013). A lack of in-channel vegetation can therefore be a limiting factor as it acts as a source of organic material to bed sediments, enhancing the denitrification capacity of the river channel. As such, river channel naturalisation schemes should seek to introduce or encourage the natural development of marginal and in-channel vegetation where possible to provide sufficient sources of OM within a river channel and help to promote N cycling.

7.2.3 Estimates of nitrogen and phosphorus removal efficiency

Studies were acquired with references to nutrient concentrations upstream and downstream of newly implemented river channel re-naturalisation schemes, as well as concentrations in a downstream location before and after construction. Factors influencing the efficiency estimates collected were predominately design related, however due to a lack of data collected, no trend or characteristic variable could be identified as the key factor delivering a certain reduction estimate value. Based on the theory and processes of removal which have been identified (see Sections 7.2.1 and 7.2.2), in principle it can be suggested that river channel re-naturalisation measures have the opportunity to reduce nutrient loads. Owing to the available data found in literature being limited, percentage efficiency estimates cannot be provided until more long-term monitoring schemes are in place to test the impact and benefit of river restoration. Calculating percentage efficacy estimates would also require more literature to quote load reductions, as opposed to concentration reductions.

Despite not finding adequate data to ascertain generic estimates for mean N and/or P reductions as a result of river channel renaturalisation, Table 7:2 shows the N removal percentage efficiency data collected on various forms of river channel re-naturalisation. This includes studies that account for seasonality, studies with a length of sampling greater than a year and studies with robust and repeatable methodologies. Having carried out a literature review, the importance of lateral connectivity on nutrient reductions was established, hence Section 7.2 predominantly concerns floodplain reconnection. However, initially all forms of river restoration were included, therefore the full database is presented below to allow for comparison. No robust studies were found regarding P removal. Since no trend or consistency could be found for N or P, site specific variables have not been included. Table 7:2 shows one study to reference concentration increase and that the N reductions range from 12.9% as the minimum, up to 56.3% as the maximum for river restoration methods. It should be noted that most studies listed below reference concentration reductions, not load reductions.

Table 7:2. Mean concentration reduction values for N from different robust studies implementing different forms of river restoration techniques. Negative percentage reductions indicate where the scheme saw an increase in N.

Study	Form of RR	Location	Form of N	Conc. or load	Mean reduction (%)
Filoso and others, (2011)	Channel reconfiguration, bank armouring, boulder placement and grade controls to increase hydraulic resistance	NE USA	TN	Conc.	33.3
Filoso and others, (2011)	Channel reconfiguration, bank armouring, boulder placement and grade	NE USA	TN	Conc.	-3.1

Study	Form of RR	Location	Form of N	Conc. or load	Mean reduction (%)
	controls to increase hydraulic resistance				
Filoso and others (2011)	Channel reconfiguration, bank armouring, boulder placement and grade controls to increase hydraulic resistance	NE USA	TN	Conc.	48.4
Filoso and others, (2011)	Regrading banks, planting riparian grasses, and placing small cobbles and stones along the stream bed	NE USA	TN	Conc.	56.3
Filoso and others, (2011)	Establishment of vegetated floodplains, step-pools, riffles, and rock weirs	NE USA	TN	Conc.	13.3
Filoso and others, (2011)	Establishment of vegetated floodplains, step-pools, riffles, and rock weirs	NE USA	TN	Conc.	12.9
Kaushal and others, (2008)	Bank stabilisation addition of sediments to channel, construction of riffles and meanders, floodplain reconnection	NE USA	NO3	Conc.	27.8
Tschikof and others, (2022)	Re-connection of floodplains	Danube Basin	TN	Load (modelled)	14.5
Kaushal and others, (2008)	Bank stabilisation addition of sediments to channel, construction of riffles and meanders, floodplain reconnection	NE USA	NO3	Conc.	21.8

Study	Form of RR	Location	Form of N	Conc. or load	Mean reduction (%)
Mayer and others, (2022)	Floodplain reconnection	NE USA	NO3	Conc.	32.9

To allow for transparency, Table 7:2 presents the studies acquired relating to N which were deemed to have robust methodologies whilst Table C:1 in Appendix 3 presents the studies without robust methodologies. All methods of river restoration were included in the search. The studies shown in Table C:1 have been rejected from the analysis due to an insufficient sample size, not accounting for seasonality, sampling for under a year or for not having a repeatable method. They are, however, useful to see the range of values acquired for N removal.

Table C:2 in Appendix 3 presents the studies relating to P removal without robust methodologies. Only one study was found which reported SRP removal efficiencies rather than TP for river restoration. The study has been rejected from the analysis due to an insufficient sample size, not accounting for seasonality, sampling for under a year and for not having a repeatable method. Therefore, it is recommended that further research and monitoring is required to estimate P removal efficiencies for river restoration methods.

Despite not finding adequate results in the literature, it is possible that well-designed river channel-renaturalisation schemes may be able to achieve successful nutrient removal results. See **Part 2**, The Framework, for more details on gaining credits via baseline and post-implementation monitoring for re-naturalisation schemes.

7.2.4 Summary of evidence

The main causes of N and P reductions following successful river channel re-naturalisation are associated with increased lateral connectivity promoting sedimentation and infiltration, increased hyporheic exchange and increased residence times. The combination of these factors provides chemical and physical reactions sufficient time to occur, therefore preventing the negative effects of partial denitrification for example. Studies implementing these key aspects have evidenced nutrient reductions when comparing nutrient concentrations upstream and downstream or before and after the channel re-naturalisation takes place.

Nutrient reduction estimates for N or P cannot be determined from the available literature. Despite the lack of robust data on removal efficiencies, evidence suggests that the success of river channel re-naturalisation measures is highly reliant on its design. As such, there is reasonable scientific confidence that if a channel re-naturalisation scheme is appropriately designed including accounting for stream hydrology, inflow concentrations, geomorphology, vegetation, lateral connectivity, and the inclusion of deposition areas etc, some level of nutrient reduction can be achieved. However, currently, it is not possible to place an upfront estimate on the nutrient removal efficiency a river channel re-naturalisation scheme is likely to achieve. See **Part 2**, The Framework document for more details to gain credits following baseline and post-implementation monitoring for re-naturalisation schemes.

7.3 Engineered logjams / beaver reintroduction

Engineered logjams can be constructed from logs, branches, or woody debris which are designed to reduce flow velocities, enhance transient storage, and trap sediments and nutrients (such as N and P) through the temporary storage of water within the stream channel (Lammers & Bledsoe, 2017). Engineered logjams mimic the processes caused by beaver dams. Within the literature these engineered solutions are referred to as leaky dams, artificial beaver dams, debris dams and logjams, and there are similarities to the introduction of large woody debris that can be part of the types of river channel re-naturalisation discussed in Section 7.2. However, the types of logjams / dams discussed in this section have the potential to cause distinct long-term changes to hydro-morphology and associated nutrient removal within river channels and thus are treated as a separate mitigation measure that falls under the umbrella of river restoration schemes. Engineered logjams are generally considered low-cost solutions in terms of installation and maintenance compared to other mitigation measures, with occasional clearing of debris and sediment required to ensure that dams to not cause a significant impoundment of water (Eden Rivers Trust, n.d.). The addition of in-stream woody debris or logs increases stream sinuosity and heterogeneity through the creation of backwaters, eddies, and pool-riffle sequences. These features encourage areas of upwelling and downwelling which aid in streambank and streambed stability, as well as dissipating energy across the channel, encouraging deposition of sediments and their associated nutrient load. Engineered log jams can therefore have value in treating additional problems such as bank erosion and channel incision (Herrera Environmental Consultants, Inc., 2006), which can both increase nutrient flux by mobilising sediment-bound nutrients. Due to risks associated with beavers not remaining in a single location, engineered logjams that replicate the effects of beaver dams are more likely to provide a nutrient mitigation solution that can be shown to last in perpetuity.

Beaver dams within watercourses can significantly alter hydrological regimes by impounding water and allowing for the cycling and retention of nutrients in ponds and pools (Butler & Malanson, 2005; Lammers & Bledsoe, 2017). Predation and reduced food supply can often lead to dam abandonment which ultimately results in collapse of the dam due to lack of regular maintenance (Pollock and others, 1995). However, within dams that remain occupied, beavers regularly maintain their own dams using mud, rocks and branches, without the need for upkeep or maintenance (Law and others, 2016). In order to achieve long lasting nutrient removal as a result of beaver influence the dams and resulting pools must be established and maintained to alter stream hydrology and geomorphology (Ecke and others, 2017). Beaver dams retain water within pools where available nutrients are removed through uptake by aquatic plants and phytoplankton. By retaining water, dams also cause slower release of waters downstream leading to greater nutrient storage within the catchment (Brazier and others, 2020). Research on the successful removal of N and P by beaver dams versus engineered solutions show varied results. Engineered solutions display greater nutrient retention, while young beaver dams display a tendency to release nutrients downstream on a seasonal basis, with the nutrient loads in runoff being an important factor in determining nutrient dynamics within beaver modified systems (Ecke and others, 2017). Further, beaver dams and ponds are evidenced to have age-dependent nutrient removal capacities as attenuation increases with the age of the system (levine & Meyer, 2014). This is due to the differing rates of organic material introduction to the system as it ages, as well as the digging activity of the beavers (Ecke and others, 2017).

7.3.1 Processes of nitrogen and phosphorus removal

Logjams can increase the capacity of a stream to remove or transform nutrients by reducing velocities and increasing sediment storage, as well as increasing hyporheic connectivity and associated nutrient cycling/retention (Roberts and others, 2007; Elosegi, and others, 2016; Lammers & Bledsoe, 2017). Logjams can also promote removal of N and P via uptake by vegetation (see Section 5.5). Increased vegetation growth can also contribute to greater surface roughness, further increasing the potential for sediment deposition and storage of associated nutrients. This process is most active during the vegetation growing season (Zhang and others, 2020). Removal of dissolved P will also be facilitated by sorption to deposited sediments (see Section 5.3). Dissolved P sorption processes are encouraged through increased contact time with particulate material, which is in turn promoted by the increase in hyporheic connectivity within the pool systems created by dams. As dams age sediment retention increases, with average discharge not being greatly affected over time (Smith and others, 2020). Dams thus have the capacity to reduce rates of sediment erosion caused by high flow events, helping to retain deposited, sediment-bound P.

Owing to the short-term nature of the predominant P removal processes (sorption to deposited sediments), these schemes cannot be suggested for long-term P removal. In the instance of heavy flooding, it is likely that the sediment bound P is remobilised back into the system. There are no design criteria which can ensure that this will not happen. As such, engineered logjams can be suggested as mitigation solutions for N, but not P.

Denitrification processes are key for N removal in rivers (see Section 5.4). Logjams facilitate these processes can therefore be important watershed-scale nitrate sinks, creating “hotspots” for denitrification by reducing flow velocities and increasing hyporheic exchange (Rosi-Marshall and others, 2005; Craig and others, 2008; Lazar and others, 2015; Groffman and others, 2005; Harrison and others, 2012). Increased hyporheic exchange increases contact time with denitrifying benthic bacteria and facilitates the oxidation of OM that is trapped by the dams (Quinn and others, 2007; Craig and others, 2008; Bernhardt & Likens, 2002).

7.3.2 Factors that affect nitrogen and phosphorus removal efficiency

The size of pools that form upstream of dams can influence the removal of N and P, with large ponds holding more sediments and associated nutrients (Puttock and others, 2018). Large and shallow ponds will result in a larger surface area to volume ratio, which in turn increases the potential for transient storage of river water and the associate nutrient cycling processes that occur in the hyporheic zone (Roberts and others, 2007). Studies have also identified that the age and sequence of logjams and ponds plays an important role in sediment and nutrient storage (Puttock and others, 2018).

The use of logjams has been identified in the UK as having benefits for a wide array of fluvial process, however careful consideration of appropriate locations to implement these options is needed. There is a need to understand the hydrology of a stream where a logjam will be deployed so that the dam structure will not be washed out during periods of high flow (Lammers & Bledsoe, 2017). As such, logjams are generally best suited to small watercourses < 2m (Eden Rivers Trust, n.d.), though suitable design and maintenance should help to ameliorate risks of logjams being washed away by high flows.

Vegetation density within the pools created behind dams will also influence nutrient retention, with N and P removal rates being positively correlated with the quantity of vegetation. This is achieved via increased vegetation/revegetation rates and the prolonged contact of nutrients with vegetation within the logjam-pool sequence (Craig and others, 2008). This further highlights the need to consider the size of the logjam relative the size of a river in order to maximise pool size without completely damming the watercourse. Additionally, a stream's NO_3 concentration appears to also have a positive relationship with its denitrification potential within organic debris dams (Groffman and others, 2005).

7.3.3 Estimates of nitrogen and phosphorus removal efficiency

The estimates of nutrient removal by logjams found in the available literature were based either on comparisons before and after implementation, upstream and downstream, or comparisons between nutrient levels in control sites and sites restored using logjams within test sites. The available data found in the literature was limited and mostly referenced concentration reductions, not load reductions. Some studies may provide limited data on the scale of nutrient removal benefits that logjam introductions may achieve, but it was not possible to derive percentage efficiency reductions for nutrient removal that could be applied to these schemes. However, the evidence reviewed does suggest that implementation of such solutions will reduce nutrient loads. It is important to note that due to lack of evidence on what reductions logjams could achieve to gain TN credits from engineered logjams (i.e. only two studies for TN) no upfront nutrient efficiency values could be determine and therefore monitoring is required to generate credits, whilst for P, engineered logjams cannot be used as NN mitigation.

Table 7:6 and Table 7:7 show percentage reductions in N and P reported in studies that met the criteria for retention in this review (monitoring period > 1 year with a robust and repeatable sampling methodology). The values found in the literature were all for beaver dams, however based on the review of wider literature, it is possible that well-designed logjams may be able to achieve the same or potentially better rates of nutrient removal. Although as previously mentioned, engineered logjams cannot be suggested as mitigation schemes for P, all studies found for P have been provided below for reference.

Table 7:3. Mean reduction values for N from different robust studies looking at beaver reintroduction

Study	Type of dam	Location	Form of N	Conc. or load	Mean reduction (%)
Law and others, (2016)	Eurasian beaver and North American beaver	Scotland, UK	Nitrate	Conc.	43.0
Puttock and others, (2017)	Eurasian beaver dam	England, UK	TN	Conc.	53.0
Correll and others, (2000)	North American beaver dam	North Carolina, USA	TN	Conc.	18.0
Dewey and others, (2022)	North American beaver dam	Colorado, USA	Nitrate	Conc.	44.2

Table 7:4. Mean reduction values for P from different robust studies looking at beaver reintroduction

Study	Type of dam	Location	Form of P	Conc. or load	Mean reduction (%)
Correll and others, (2000)	North American beaver dam	North Carolina, USA	TP	Conc.	21.0
Puttock and others, (2017)	Eurasian beaver dam	England, UK	PO4	Conc.	72.0

Table C:3 in Appendix 3 shows mean reduction in nitrate achieved by a study that was not deemed to have robust methodologies. This study provides further general support for the principle that logjams can achieve nutrient removal. There were no further studies found which reported on the removal efficiencies of P from logjams or beaver reintroduction.

7.3.4 Summary of evidence

A reduction in N concentrations following the implementation of logjams or beaver reintroduction is associated with the creation of a more heterogenous and sinuous stream environment. This is achieved through the introduction of porous dams which increase transient storage, hyporheic exchange, and hydrological residence times as a result of flow reductions behind the dams. These factors together allow for active N cycling and P deposition and sorption processes to occur. Studies which have emulated the natural conditions typically created by beavers have evidenced nutrient reductions, though a lack of long-term monitoring means that is unclear how these schemes will perform over long time periods. There is significant scientific confidence that a correctly designed scheme – which takes into consideration stream hydrology and inflow nutrient concentrations – can achieve some level of N and P reduction. Due to the lack of studies, TN credits from logjams cannot be claimed upfront due to the large uncertainties in the nutrient removal efficiencies, monitoring to evidence the reduction will be needed. However, for P due to the uncertainties over whether the reductions are temporary this measure cannot currently be used as NN mitigation.

7.4 Agroforestry

Agroforestry is a farming system where trees are planted within the areas used for arable food or livestock production and these two types of agroforestry are often termed silvo-pasture, i.e. the incorporation of trees within areas of livestock pastures, and silvo-arable farming, i.e. the incorporation of trees within areas of arable agriculture. Agroforestry is the overarching term for these farming styles, designed to optimise the benefits derived from natural biological processes within a farmed landscape (Briggs, 2012). It is a long-term solution to land availability, declining crop yields and biodiversity, whilst simultaneously maintaining, and potentially increasing, the productivity of agricultural land. Typically, the returns for single type of agriculture (i.e. type of livestock or arable crop) involved are lower than if they were carried out intensively, however the combination provides a diversification of yields and income for the farmer as the trees should provide alternative sources of crops.

This review has not found examples of agroforestry being implemented for the specific goal of nutrient mitigation; however, research suggests it can deliver nutrient mitigation benefits (Michel and others, 2007; Briggs, 2012; Franklin and others, 2016). The majority of available agroforestry research concerning nutrient reductions relates to silvo-arable farming, therefore this report largely focusses on this type of agroforestry, though the nutrient removal processes are almost identical silvo-pasture farming.

It is also noted that orchards and short-rotation coppice (SRC) can be applied on arable land as an alternative type of silvo-arable system for nutrient mitigation (Guenon and others, 2016), with the crops providing food or biomass fuel, respectively. Orchards and SRC have previously been suggested in consultancy reports to provide practical solutions to nutrient removal (TerraConsult, 2018; Ricardo, 2021b). In addition to being implemented as a land use change option, orchards and SRC can serve to scavenge P from the soil on small-scale PTP developments. Where orchards typically relate to the cultivation of fruit and nut trees, SRC systems relate to the cultivation of fast-growing crops to produce biomass fuel and other sustainable wood products (Forest Research, 2022; Woodland Trust, 2022). In both systems N and P is removed from the system via the cultivation and export of harvested fruits and coppice (biomass).

For agroforestry solutions to be adopted, they must be accessible and beneficial to farmers in order to increase their likelihood of long-term cooperation. Fortunately, agroforestry is a highly customisable solution with flexibility to suit the needs of landowners/land managers. There is a variety of different considerations, such as tree choices and the value of their returns, species combinations (leafing time of canopy species, potential livestock consumption of trees, pests) and the design layout of the system (Raskin & Osborn, 2019). This report will not go into detail on these matters as they have little effect on the nutrient removal capacity of the system, however they will affect the financial returns of a farm and thus are relevant for practical reasons.

It is worth briefly noting the reasons for which a farmer would consider implementing agroforestry as a nutrient mitigation solution. In most circumstances, similar levels of arable and livestock productivity are maintained whilst additional products such as wood fuel, timber and other crops, e.g. fruit and nuts, are produced for sale, providing additional income (Raskin & Osborn, 2019). Furthermore, depending on the tree choices, profits can be increased with the potential for stable returns from tree crops within 5 years (Briggs, 2012). This provides farmers with a diversified seasonal income. Additionally, once mature, agroforestry is designed to be a relatively self-sustaining ecosystem. This ensures that while the system is active, there is little to no dependency upon the farmer to carry out maintenance to secure nutrient mitigation, above harvesting of biomass as part of standard cropping practices.

There are also extensive environmental benefits beyond nutrient capture, including livestock health and reduced stress, carbon sequestration, reduced soil degradation and improved nutrient cycling through mycorrhizal associations (Raskin & Osborn, 2019). In addition, SRC systems may be able to provide community-level benefits is energy crops are used to provide combined neighbourhood energy and nutrient neutrality schemes.

7.4.1 Processes of nitrogen and phosphorus removal

From the perspective of nutrient mitigation, the key difference between standard agricultural land management and agroforestry is the presence of phreatophitic trees that can access previously inaccessible nutrients. This is applicable to both silvo-arable and silvo-pasture systems. Vegetative (including for example Orchards and SRC) uptake of nutrients is therefore a key mechanism by which N and P are removed from the soil system. SRC removes P via the export of harvested coppice (biomass) containing P; with orchards removing P via the export of harvested fruit (e.g., apples) containing P. SRC systems and orchards can thus be considered as a solution to the P legacy issue, enabling accumulated soil P to be directly removed from the system. Both P and N can be removed from soils via vegetative uptake processes (see Section 5.5), though there is less research on N removal by orchards and SRC systems.

The process of vegetative uptake is seasonally dependent and has potential to be reversible, therefore considerations regarding plant species are essential. Ash, for example, is leafless for a large proportion of the year, therefore requiring minimal nutrient uptake for conversion to biomass (Raskin & Osborn, 2019). Agricultural plants typically have shallow root systems, causing significant leaching of nutrients located deeper in the soil profile. Trees inhibit this leaching through uptake and conversion to biomass without the consequence of extra competition due to the varying root depths. As a result, there is a reduced requirement for nitrate and phosphate fertilisers, reducing the overall input into the soil system. The extended root systems also increase beneficial mycorrhizal associations within the soils, further increasing plant N and P uptake. Denitrification rates are increased with the addition of trees due to an increased source of OM to the soil (Lehmann & Schroth, 2003), with the OM acting as an energy source for denitrifying bacteria (see Section 5.4). This process is a long-term solution, permanently converting NO_3 to gaseous forms of N (Franklin and others, 2016).

Sediment bound nutrients are not only removed from the system through plant uptake but also retained within the system due to reduced wind erosion resulting from the shelter beltlike formation of tree rows. Acting as windbreaks, the immediate micro-climate is modified to reduce wind velocities and the subsequent energy available for sediment transportation (Briggs, 2012). Such windbreaks also increase the local surface roughness and uptake capacity of water, decreasing surface water runoff and helping to retain sediment-bound nutrients. The improved drainage and infiltration support subsurface P adsorption whilst reducing flow velocities to support the completion of chemical P removal processes.

7.4.2 Factors that affect nitrogen and phosphorus removal efficiency

Consideration of the tree species and its leafing period is essential for optimising yields as well as nutrient uptake in silvo-arable agriculture. As trees increase in size, the competition with agricultural crops for light and water has the potential to cause decreases in crop yields (Raskin & Osborn, 2019). Poor choice of species combinations will reduce the nutrient uptake of crops, whilst negating the underlying purpose of agroforestry.

Tree growth rates can impact the removal of P from the soil system; thus, the choice of tree species is an important environmental consideration. In SRC systems, fast growing trees such as poplar and willow - which can regrow quickly after harvesting – are therefore typically selected. The quicker that the trees grow and can be harvested, the more N and P can be removed from the system and exported in coppice (biomass). In orchards, the type of fruit tree species (e.g., apple vs fig) as well as fruit species (e.g., Braeburn apple vs cox apple) have been evidenced to influence P removal rate (Palmer & Dryden, 2006). As these factors influence the rate of nutrient uptake by vegetation, it can be assumed that they also effect the rate of N removed from soils via this process, though specific evidence on N accumulation in biomass has not been found.

N and P removal efficiency can be majorly influenced by the design of the agroforestry system. The Agroforestry Handbook contains key design criteria for optimising yields as well as nutrient retention, with a balance between these requirements recommended (Raskin & Osborn, 2019). For example, a tree density of 100/ha is suggested to provide a successful balance between financial and environmental benefits. This density should not significantly reduce yields from the primary agricultural output and still result in nutrient retention advantages. A greater planting density is expected to further increase denitrification and N and P adsorption / uptake processes, though agricultural yields would likely decrease as tree density increases.

Environmental considerations such as the maturity of the system also has an impact on nutrient retention capabilities. As trees age, they tend to be more effective at taking up water and reducing run-off (George & Marschner, 1996). Consequently, the efficiency of the system’s nutrient retention mechanisms may increase with age, suggesting agroforestry to be an effective long-term mitigation solution. Soil type and soil conditions will also have an impact on retention capacities, with clay soils providing more sites for P sorption and anoxic conditions promoting denitrification (see Sections 5.3 & 5.4). In addition, the existing P content of the soil can provide a source of nutrient for removal by agroforestry practices such as SRC, which if implemented on land with high soil P content (e.g., former arable land or on riparian buffers) provides a potential means for removal of legacy P (Ricardo, 2021b). Literature also suggests a low slope and permeable conditions to be beneficial in encouraging infiltration by promoting lower flow velocities, providing time for chemical processes to remove nutrients from the environment.

7.4.3 Estimates of nitrogen and phosphorus removal efficiency

Studies were acquired for both silvopasture and silvo-arable agroforestry systems to provide data for nutrient concentrations of inflowing and outflowing overland flows and subsurface flows. The percentage reductions are based on either a comparison between a nearby control site of exclusively pasture or arable farming and the agroforestry site, nutrient concentrations above and below the site, or a temporal difference between pre- and post-implementation of agroforestry. Percentage reductions were calculated based off these values to establish nutrient reduction values which can be expected to be achieved under successful implementation of agroforestry schemes. The two forms of agroforestry have been separated in this section.

Nitrate and TP were identified as favourable nutrient types to be examined in order to remain consistent with Farmscoper as it is expected that Farmscoper would typically be used to model nutrient loading to agroforestry schemes. TP was chosen to account for all forms of P in the receiving environment for agroforestry however no studies were found for silvopasture TP removal. As such, other studies with different forms of P have been included in the tables below to show some example values of P removal. In addition, the available data found in the literature was limited and often referenced concentration reductions, not load reductions. The data supports the principle that agroforestry can provide nutrient mitigation benefits, but it also highlights the wide range in the scale of nutrient removal the schemes may deliver.

7.4.3.1 Silvopasture nutrient removal efficiencies

Owing to the lack of any robust data, no efficacy reduction percentages for TP or nitrate have been determined for silvopasture schemes. No studies were found with robust methodologies, therefore there is not enough certainty to be able to claim credits upfront. With robust baseline and post-implementation monitoring however (as explained in **Part 2**), realistic credits for TP and / or nitrate can be allocated following the implementation of the scheme.

Although precautionary removal efficiency vales are unable to be derived due to a lack of literature, Table C:4 and Table C:5 in Appendix 3 show some non-robust data which were found.

7.4.3.2 Silvo-arable nutrient removal efficiencies

Table 7:9 presents the reduction values for TP from different studies looking at silvo-arable agroforestry. It should be noted that the crop types studied in Table 7:9 are not representative of UK agriculture. Therefore, the efficiency of a UK-based agroforestry system to reduce nutrient loading could vary considerably. No robust studies were found for nitrate. . Due to the lack of robust data no efficacy reduction percentages have been able to be determined, therefore credits cannot be claimed upfront. For clarity, the non-robust data has been provided in table C:6 for nitrate and C:7 for phosphorus in Appendix 3.

Table 7:9. Mean reduction values for P from different robust studies looking at silvo-arable agroforestry

Study	Type of silvo-arable	Location	Form of P	Conc. or load	Mean reduction (%)
Xia and others, (2016)	Wheat, peanut and alfalfa hedgerow	China	TP	Load	67.6
Xia and others, (2016)	Wheat, peanut and *toona sinensis*	China	TP	Load	64.0

7.4.3.3 Summary

Soil type was the key environmental variable that could be isolated between the different studies in the limited dataset. Notably, the lowest nitrate and TP reductions were reported for sandy loam soils whereas the highest were reported for silt loam soils (both on silvo-arable farms). Overall sandy soils had lower removal efficiencies compared to heavier soils. This is to be expected as less free draining soils will increase water retention times and thus promote denitrification and P sorption to soils.

Given the lack of data for silvopasture, it is hard to make assumptions regarding the most efficient type of agroforestry. Although there appears to be a possible link between soil type and nutrient reductions, there was not enough data on other driving variables to ascertain what other factors may be key for achieving high nutrient reduction percentages. Some of the studies found were also carried out over short sampling periods of less than a year. These studies and studies that were not explicit about their sampling time were rejected. As a result, only methodologies which accounted for seasonality were included.

7.4.4 Summary of evidence

Agroforestry aims to utilise tree planting within agricultural landscapes to trap nutrients that would otherwise leach or run-off into local river systems or groundwater. The key nutrient retention mechanisms in agroforestry are denitrification, plant uptake and reduced wind-erosion of nutrient bound soils; all of which have the capacity to permanently reduce the need for N and P based fertilisers. To effectively implement this solution, careful consideration of species type, and species combinations to reduce competition is required. Additionally, certain design requirements need to be considered, as well as rooting depths, soil type, gradient, shading and importantly tree density. A balance needs to be met between maintaining agricultural yields without competition and optimising nutrient retention with heightened tree densities. This balance can most easily be kept through making economic decisions regarding plant species (high value yields with high nutrient assimilation capacities) as well as through coppicing. No precautionary values for nitrate or TP in silvopasture or silvo-arable systems were able to be derived due to a lack of robust data.

8. Conclusion

NbS provide a range of options that can be used to provide nutrient mitigation as part of strategies to address nutrient neutrality. This report has provided a review of different NbS in order to ascertain whether there is a body of evidence that supports the theory behind how each NbS provides mitigation. The NbS chosen for review were:

- **River channel re-naturalisation**
- **Riparian buffers**
- **Engineered logjams**
- **Agroforestry**

For each of these solutions, a literature review was conducted to ascertain whether the evidence base for a given solution allows for the estimate of a suitably precautionary nutrient reduction percentage estimate if the solution is correctly implemented. This report comprises Part 1 of a three-part project that will provide a decision support framework and associated tools to support NE staff in the assessment of nutrient mitigation proposals. The outputs from this review will be applied within a decision support framework in Part 2 of this project.

Each of the above NbS were addressed separately using a methodology that sought to determine whether there are key environmental variables that determine their nutrient removal efficacy; whether the studies for each NbS followed robust methodologies; and whether the type of N and P fractions reported in studies allowed for cross-comparison between different papers.

Buffer strips were found to have a sufficient evidence base to support precautionary estimates for N and P removal; 10-36% and 22-43%, respectively. However, the other NbS (river channel re-naturalisation, logjams and agroforestry) did not have adequate supporting evidence for nutrient reduction estimates. There was a lack of studies referencing load reductions that enabled robust estimates of percentage efficiencies of nutrient removal for these NbS. Where estimates were possible, rejection of various studies due to methodological limitations meant that these estimates were subject to uncertainty. It is recommended that further monitoring is carried out for these NbS to more accurately determine nutrient removal efficiencies.

Table 8:1.1 Summary of maximum N and P removal efficiencies which can be claimed up front – See Part 2 (The Framework) for how to determine whether the full maximum value can be claimed.

NbS	Forms of N and P	N removal efficiency (%)	P removal efficiency (%)
Riparian buffers	Nitrate, TP	10-36% depending on width	22-43% depending on width
River channel re-naturalisation	TN, TP	Monitoring required	Monitoring required
Engineered logjams	TN	Monitoring required	N/A
Silvopasture	Nitrate, TP	Monitoring required	Monitoring required
Silvo-arable	Nitrate, TP	Monitoring required	Monitoring required

A subset of the literature found on these solutions was used to estimate percentage nutrient removal efficiencies from studies that accounted for seasonal variability, which impacts the efficacy of NbS for nutrient mitigation. The lowest nutrient removal efficiencies were taken from these retained studies. These precautionary estimates are aimed at accounting for long-term changes in the efficacy of a scheme in face of a changing climate and reductions in nutrient inputs that are likely to occur as agricultural practices improve. Naturally the influent concentration is not the only variable needed to understand load reduction. However, it is important to note that to claim all or part of these credits upfront, **Part 2** (The Framework) must be followed.

For most of the NbS that were reviewed in this study, it was not possible to determine a percentage efficiency nutrient removal estimate. This was either due to a lack of research; due to studies not being conducted in a manner that allowed the efficacy of a given solution to be described with a percentage removal efficiency; and/or due to studies not being conducted over long enough time periods to have confidence in their output. Furthermore, it is recognised (as highlighted throughout this document) that appropriate design and understanding of the local environmental condition is critical to providing the best opportunity for nutrient benefit. Whilst these solutions could still be deployed as nutrient mitigation schemes based on the information provided from this review of the literature, gaps in knowledge remain. As such any NbS approach to nutrient mitigation would need to include a bespoke monitoring programme to determine the amount of nutrient mitigation being delivered on a kg/yr basis.

For each of the NbS assessed in this study, the review sought to also determine what environmental and design factors may result in optimal nutrient reduction performance for a given solution. All solutions had some key design factors that play a key role in their nutrient removal efficiency. Riparian buffers should be at least 6-10 m wide, and it is likely that a wooded buffer will provide greater certainty that they will retain their nutrient mitigation benefits in perpetuity. River channel re-naturalisation schemes should follow the general guiding principles of how to restore river channel habitats to a more natural form, aiming to maximise habitat heterogeneity and floodplain connectivity in order to maximise the processes that immobilise nutrients. Similarly, logjams are likely to perform best when the size of pools upstream of dams can be maximised. And finally, agroforestry scheme should aim for higher tree planting densities and may perform best on fine grained soils.

As well as the assessment of the above NbS to determine their efficacy as nutrient removal solutions, this study also assessed the veracity of the nutrient export coefficients that are used to determine the background N and P export from mitigation schemes that convert agricultural land to semi-natural habitats. The review of these coefficients found that although they are subject to uncertainty and that evidence suggests different semi-natural habitats will have slight difference in their background nutrient export, there was not sufficient evidence to provide a credible single alternative to the export coefficients that are currently in use. However, further accuracy in N export coefficients could likely be achieved if local N deposition rates are taken into account.

All the research conducted in this review highlighted that NbS for nutrient mitigation generally has a limited evidence base that can be used to determine the scale of nutrient reductions a scheme could deliver in terms of a percentage reduction in nutrient load. Furthermore, most studies do not account for potential future changes in N and P loading from agricultural sources that are likely to reduce the scale of N and P sources entering NbS as agricultural practices improve over time. This suggests a need to account for these changes in the way in which nutrient inputs to NbS are calculated through further monitoring, modelling or both. Many studies also do not account for climate change.

It should be emphasised that the NbS investigated here can provide value beyond just nutrient mitigation potential. The NbS detailed in this review can provide an array of additional benefits including natural flood management, biodiversity net gain and carbon sequestration. In order to maximise the wider environmental benefits that nutrient neutrality can deliver, it will be important to conduct further research to determine more robust estimates of the efficacy of NbS for nutrient mitigation and thus improve the strength of recommendations that can be made for these solutions.

The following areas for further research are recommended:

- Studies that focus on nutrient load reduction as well as concentration change in flows of water entering and exiting NbS.
- The implementation of NbS nutrient mitigation schemes using extremely precautionary load reductions to allow for long-term bespoke monitoring of schemes that explicitly account for the seasonal variation of nutrient mitigation.
- The development of an open-source repository for monitoring data on NbS that are implemented for nutrient reduction purposes and monitored to assess their performance.
- Further research to provide an understanding of the potential impact of legacy P on nutrient reduction estimates.
- A systematic analysis of key environmental variables that may impact nutrient removal efficacy for each solution.
- Development of more robust models to estimate the input of N and P to a mitigation solution.

The above research should help to further the application of NbS for nutrient mitigation and thus help to provide benefits to the wider restoration of river catchments in the process.

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Appendix 1: Research Metadata

Table A:1. Nutrient export from semi-natural habitats research metadata (N/A refers to sources which were not found online)

Search engine	Search string	Document title	URL
Google Scholar	Nitrogen deposition semi-natural habitats	Can on-site management mitigate nitrogen deposition impacts in non-wooded habitats?	Can on-site management mitigate nitrogen deposition impacts in non-wooded habitats? - ScienceDirect
Google Scholar	Nitrogen deposition semi-natural habitats	Effects of enhanced nitrogen deposition and phosphorus limitation on nitrogen budgets of semi-natural grasslands	Effects of enhanced nitrogen deposition and phosphorus limitation on nitrogen budgets of semi-natural grasslands - Phoenix - 2003 - Global Change Biology - Wiley Online Library
Google Scholar	Nitrogen deposition semi-natural habitats	How long do ecosystems take to recover from atmospheric nitrogen deposition?	How long do ecosystems take to recover from atmospheric nitrogen deposition? - ScienceDirect
Google Scholar	Nitrogen deposition semi-natural habitats	Habitat Management: A Tool to Modify Ecosystem Impacts of Nitrogen Deposition?	Habitat Management: A Tool to Modify Ecosystem Impacts of Nitrogen Deposition? (hindawi.com)

Search engine	Search string	Document title	URL
Google Scholar	Nitrogen deposition semi-natural habitats	Review of the effectiveness of on-site habitat management to reduce atmospheric nitrogen deposition impacts on terrestrial habitats	Review of the effectiveness of on-site habitat management to reduce atmospheric nitrogen deposition impacts on terrestrial habitats - NERC Open Research Archive
Google Scholar	P export coefficient modelling	Phosphorus Loading in the Frome Catchment, UK: Seasonal Refinement of the Coefficient Modeling Approach	Phosphorus Loading in the Frome Catchment, UK: Seasonal Refinement of the Coefficient Modeling Approach - Hanrahan - 2001 - Journal of Environmental Quality - Wiley Online Library
Google Scholar	Nitrogen deposition and fixation	Irrigation and fertiliser strategies for minimising nitrogen leaching from turfgrass	Irrigation and fertiliser strategies for minimising nitrogen leaching from turfgrass - ScienceDirect
Google Scholar	P uptake rates by soils	Phosphorus content in soil, uptake by plants and balance in three European long-term field experiments	Phosphorus content in soil, uptake by plants and balance in three European long-term field experiments | SpringerLink
Google Scholar	Terrestrial N deposition	Atmospheric nitrogen deposition in terrestrial ecosystems: Its impacts on plant communities and consequences across trophic levels	Atmospheric nitrogen deposition in terrestrial ecosystems: Its impact on plant communities and consequences across trophic levels - Stevens - 2018 - Functional Ecology - Wiley Online Library
Google Scholar	Nitrogen forest	Nitrogen saturation in temperate forest ecosystems	Nitrogen Saturation in Temperate Forest Ecosystems | BioScience | Oxford Academic (oup.com)

Search engine	Search string	Document title	URL
Google Scholar	Nitrogen leaching	Predicting dissolved inorganic nitrogen leaching in European forests using two independent databases	Predicting dissolved inorganic nitrogen leaching in European forests using two independent databases - ScienceDirect
Google Scholar	Nitrogen flux grassland	Nitrate leaching and nitrous oxide flux in urban forests and grasslands	Nitrate leaching and nitrous oxide flux in urban forests and grasslands - PubMed (nih.gov)
Google Scholar	Nitrogen leaching	Do indicators of nitrogen retention and leaching differ between coniferous and broadleaved forests in Denmark?	Do indicators of nitrogen retention and leaching differ between coniferous and broadleaved forests in Denmark? - ScienceDirect
Google Scholar	Nitrogen and Phosphorus retention capacities	Contrasting nitrogen and phosphorus budgets in urban watersheds and implications for managing urban water pollution	Contrasting nitrogen and phosphorus budgets in urban watersheds and implications for managing urban water pollution - PubMed (nih.gov)
Google Scholar	Legacy phosphorus in waterbodies	Water Quality Remediation Faces Unprecedented Challenges from “Legacy Phosphorus”	Water Quality Remediation Faces Unprecedented Challenges from “Legacy Phosphorus” | Environmental Science & Technology (acs.org)
Google Scholar	P export coefficient modelling	Evaluation and management of the impact of land use change on the nitrogen and phosphorus load delivered to surface waters: the export coefficient modelling approach	Evaluation and management of the impact of land use change on the nitrogen and phosphorus load delivered to surface waters: the export coefficient modelling approach - ScienceDirect

Search engine	**Search string**	**Document title**	**URL**
Google Scholar	Nutrient leaching groundwater contamination	Chapter 7 Nutrient Leaching	Nutrient leaching. | Trees, crops and soil fertility: concepts and research methods (cabidigitallibrary.org)
Google Scholar	Nitrate leaching forests	Nitrogen input together with ecosystem nitrogen enrichment predict nitrate leaching from European forests	Nitrogen input together with ecosystem nitrogen enrichment predict nitrate leaching from European forests - MacDonald - 2002 - Global Change Biology - Wiley Online Library
Google Scholar	Terrestrial N deposition	The globalization of nitrogen deposition: consequences for terrestrial ecosystems	The globalization of nitrogen deposition: consequences for terrestrial ecosystems - PubMed (nih.gov)
Google Scholar	Atmopsheric nitrogen deposition	Trends and variability in weather and atmospheric deposition at UK Environmental Change Network sites (1993–2012)	Trends and variability in weather and atmospheric deposition at UK Environmental Change Network sites (1993–2012) - ScienceDirect
N/A	N/A	Advice on achieving nutrient neutrality for new development in the Solent region	Solent-Nutrients-V5-June2020.pdf (newforestnpa.gov.uk)
Google Scholar	Nitrogen deposition semi-natural habitats	Disparities between plant community responses to nitrogen deposition and critical loads in UK semi-natural habitats	Disparities between plant community responses to nitrogen deposition and critical loads in UK semi-natural habitats - ScienceDirect

Search engine	Search string	Document title	URL
Google Scholar	Nitrogen deposition heathland	Ecosystem recovery: heathland response to a reduction in nitrogen deposition	Ecosystem recovery: heathland response to a reduction in nitrogen deposition - POWER - 2006 - Global Change Biology - Wiley Online Library
Google Scholar	Phosphorous export budget	A phosphorus budget for Northern Ireland: inputs to inland and coastal waters	A phosphorus budget for Northern Ireland: inputs to inland and coastal waters - ScienceDirect
Jstor	Nitrogen deposition peatland	Waterborne Nutrient Flow Through an Upland-Peatland Watershed in Minnesota	Waterborne Nutrient Flow Through an Upland-Peatland Watershed in Minnesota on JSTOR
Google Scholar	Nitrogen deposition semi-natural habitats	Modelling the effect of forest cover in mitigating nitrate contamination of groundwater: A case study of the Sherwood Sandstone aquifer in the East Midlands, UK	Modelling the effect of forest cover in mitigating nitrate contamination of groundwater: A case study of the Sherwood Sandstone aquifer in the East Midlands, UK - ScienceDirect
Google Scholar	Nitrogen retention soils	Synchronous sequestration of organic carbon and nitrogen in mineral soils after conversion agricultural land to forest	Synchronous sequestration of organic carbon and nitrogen in mineral soils after conversion agricultural land to forest - ScienceDirect
Google Scholar	Groundwater N losses	Nitrate-nitrogen losses to groundwater from rural and suburban land uses	Nitrate-nitrogen losses to groundwater from rural and suburban land uses | Journal of Soil and Water Conservation (jswconline.org)

Table A:2. General nutrient mitigation metadata (N/A refers to sources which were not found online)

Search engine	Search string	Document title	URL
Google Scholar	Soil denitrification factors	Denitrification in soil. II. Factors affecting denitrification	Denitrification in soil. II. Factors affecting denitrification | The Journal of Agricultural Science | Cambridge Core
Google Scholar	Soil denitrification factors	Nitrification in acid soils: micro-organisms and mechanisms.	Nitrification in acid soils: micro-organisms and mechanisms. - Abstract - Europe PMC
Google Scholar	Soil P removal	Reduction of High Soil Test Phosphorus by Corn and Soybean Varieties	Reduction of High Soil Test Phosphorus by Corn and Soybean Varieties | Agronomy Journal (wiley.com)
Google Scholar	Transient storage nutrients	In-channel transient storage and associated nutrient retention: Evidence from experimental manipulations	In-channel transient storage and associated nutrient retention: Evidence from experimental manipulations - Ensign - 2005 - Limnology and Oceanography - Wiley Online Library
Google Scholar	Phosphorus cycling rivers	Phosphorus cycling in rivers	Phosphorus cycling in rivers - GOV.UK (www.gov.uk)
N/A	N/A	Fine Sediment Pressure Narrative	fine-sediment-pressure-rbmp-2021.pdf (environment-agency.gov.uk)

Search engine	Search string	Document title	URL
Google Scholar	Nitrogen cycling forests	Various players in the nitrogen cycle: Diversity and functions of the microorganisms involved in nitrification and denitrification	Full article: Various players in the nitrogen cycle: Diversity and functions of the microorganisms involved in nitrification and denitrification (tandfonline.com)
Google Scholar	Phosphorus sorption rivers	Phosphorus sorption–desorption behaviour of river bed sediments in the Abshineh river, Hamedan, Iran, related to their composition	Phosphorus sorption–desorption behaviour of river bed sediments in the Abshineh river, Hamedan, Iran, related to their composition | SpringerLink
Google Scholar	Phosphorus sorption rivers	Phosphorus Sorption Characteristics of Flooded Soils	Phosphorus Sorption Characteristics of Flooded Soils - Khalid - 1977 - Soil Science Society of America Journal - Wiley Online Library
Google	equilibrium phosphorus concentrations	Evaluation of base solutions to determine equilibrium phosphorus concentrations (EPC0) in stream sediments	[PDF] Evaluation of base solutions to determine equilibrium phosphorus concentrations (EPC0) in stream sediments | Semantic Scholar
Google Scholar	Phosphorus sorption rivers	Phosphorus in rivers	Phosphorus in rivers — ecology and management - ScienceDirect
Google Scholar	Nature based solutions nitrogen	Diffuse Water Pollution from Agriculture: A Review of Nature-Based Solutions for Nitrogen Removal and Recovery	Water | Free Full-Text | Diffuse Water Pollution from Agriculture: A Review of Nature-Based Solutions for Nitrogen Removal and Recovery (mdpi.com)

Search engine	Search string	Document title	URL
Google Scholar	Soil denitrification factors	A global synthesis of soil denitrification: Driving factors and mitigation strategies	A global synthesis of soil denitrification: Driving factors and mitigation strategies - ScienceDirect
Jstor	River nutrient dynamics	Dissolved Organic Carbon Enrichment Alters Nitrogen Dynamics in a Forest Stream	Dissolved Organic Carbon Enrichment Alters Nitrogen Dynamics in a Forest Stream on JSTOR
Google Scholar	Hyporheic exchange processes	The ecological significance of exchange processes between rivers and groundwater	The ecological significance of exchange processes between rivers and groundwater - BRUNKE - 1997 - Freshwater Biology - Wiley Online Library
Google Scholar	Legacy phosphorus grassland	Impact of legacy soil phosphorus on losses in drainage and overland flow from grazed grassland soils	Impact of legacy soil phosphorus on losses in drainage and overland flow from grazed grassland soils - ScienceDirect
Google	The phosphorus cycle	Phosphorus basics - the phosphorus cycle	(PDF) Phosphorus basics - the phosphorus cycle (researchgate.net)
Google	Phosphorus sorption rivers	Phosphorus sorption characteristics of estuarine sediments under different redox conditions	Phosphorus sorption characteristics of estuarine sediments under different redox conditions - PubMed (nih.gov)

Search engine	Search string	Document title	URL
Google Scholar	Phosphorus sorption rivers	Phosphate release and sorption by soils and sediments: effect of aerobic and anaerobic conditions	Phosphate release and sorption by soils and sediments: effect of aerobic and anaerobic conditions - PubMed (nih.gov)
Google Scholar	Nitrogen cycling rivers	Basic Principles and Ecological Consequences of Changing Water Regimes on Nitrogen Cycling in Fluvial Systems	Basic Principles and Ecological Consequences of Changing Water Regimes on Nitrogen Cycling in Fluvial Systems | SpringerLink
Google	Sediment retention rivers	Factors influencing retention of coarse particulate organic matter in streams	Factors influencing retention of coarse particulate organic matter in streams - Quinn - 2007 - Earth Surface Processes and Landforms - Wiley Online Library
Google Scholar	Phosphorus sorption rivers	Phosphorus Sorption Capacities of Wetland Soils and Stream Sediments Impacted by Dairy Effluent	Phosphorus Sorption Capacities of Wetland Soils and Stream Sediments Impacted by Dairy Effluent - Reddy - 1998 - Journal of Environmental Quality - Wiley Online Library
Google Scholar	Nitrogen cycling rivers	Ammonium Diffusion as a Factor in Nitrogen Loss from Flooded Soils	Ammonium Diffusion as a Factor in Nitrogen Loss from Flooded Soils - Reddy - 1976 - Soil Science Society of America Journal - Wiley Online Library
N/A	N/A	Nutrient Neutrality Generic Methodology	Nutrient Neutrality Generic Methodology - NECR459 (naturalengland.org.uk)

Search engine	Search string	Document title	URL
N/A	N/A	Herefordshire Council Interim Phosphate Delivery Plan Stage 2 Non-Technical Summary	Herefordshire Council Interim Phosphate Delivery Plan Stage 2 Non-Technical Summary
Google Scholar	Phosphorus assimilation	Phosphorus Uptake by Plants: From Soil to Cell	Phosphorus Uptake by Plants: From Soil to Cell | Plant Physiology | Oxford Academic (oup.com)
Google Scholar	Nitrification and denitrification	Nitrification and denitrification as sources of nitric oxide and nitrous oxide in a sandy loam soil	Nitrification and denitrification as sources of nitric oxide and nitrous oxide in a sandy loam soil - ScienceDirect
Google Scholar	Soil nutrient adsorption	Estimating soil ammonium adsorption using pedotransfer functions in an irrigation district of the North China Plain	Estimating soil ammonium adsorption using pedotransfer functions in an irrigation district of the North China Plain - ScienceDirect
Google	Sources phosphorus rivers	Updating the Estimate of the Sources of Phosphorus in UK Waters	AIC | Updating the Estimate of the Sources of Phosphorus in UK Waters (agindustries.org.uk)

Table A:3. Buffer strip research metadata (N/A refers to sources which were not found online)

Search engine	Search string	Document title	URL
Google Scholar	Riparian nutrient retention	Nutrient Retention in Riparian Ecotones	Nutrient Retention in Riparian Ecotones on JSTOR
Google	Buffer strip pollutant removal	Performance of a narrow buffer strip in abating agricultural pollutants in the shallow subsurface water flux	Performance of a narrow buffer strip in abating agricultural pollutants in the shallow subsurface water flux - ScienceDirect
Google	Riparian buffer strip agricultural pollution	Mitigating diffuse water pollution from agriculture: Riparian buffer strip performance with width	Mitigating diffuse water pollution from agriculture: riparian buffer strip performance with width. (cabi.org)
Google	Riparian buffer strip agricultural pollution	Reducing pollution from forestry related activities in the Galloway and Eskdalemuir forests: A review of Best Management Practices to reduce diffuse pollution	CREW_Reducing pollution from forestry.pdf
Google Scholar	Vegetated riparian buffer strips nitrate	Groundwater Nitrate Dynamics in Grass and Poplar Vegetated Riparian Buffer Strips during the Winter	Groundwater Nitrate Dynamics in Grass and Poplar Vegetated Riparian Buffer Strips during the Winter - Haycock - 1993 - Journal of Environmental Quality - Wiley Online Library

Search engine	Search string	Document title	URL
Google Scholar	Buffer strip phosphorus retention	DISSOLVED PHOSPHORUS RETENTION IN BUFFER STRIPS: INFLUENCE OF SLOPE AND SOIL TYPE	Dissolved phosphorus retention in buffer strips: influence of slope and soil type : Rothamsted Research
Google Scholar	Buffer strip nitrogen removal	Nitrogen removal in buffer strips along a lowland stream in the Netherlands: a pilot study	Nitrogen removal in buffer strips along a lowland stream in the Netherlands: a pilot study - ScienceDirect
Google	Buffer strip nitrate and phosphorus removal	The Use of Grassed Buffer Strips to Remove Pesticides, Nitrate and Soluble Phosphorus Compounds from Runoff Water	The Use of Grassed Buffer Strips to Remove Pesticides, Nitrate and Soluble Phosphorus Compounds from Runoff Water - Patty - 1997 - Pesticide Science - Wiley Online Library
Google	Buffer strip agricultural pollutants	Performance of a narrow buffer strip in abating agricultural pollutants in the shallow subsurface water flux	Performance of a narrow buffer strip in abating agricultural pollutants in the shallow subsurface water flux - ScienceDirect
Jstor	Buffer strip nitrogen retention	Shallow groundwater nitrogen and denitrification in a newly afforested, subirrigated riparian buffer	Shallow groundwater nitrogen and denitrification in a newly afforested, subirrigated riparian buffer on JSTOR
Google Scholar	Nitrogen load reductions buffer strips	Nitrate–nitrogen reduction by established tree and pasture buffer strips associated with a cattle feedlot effluent disposal area near Armidale, NSW Australia	Nitrate–nitrogen reduction by established tree and pasture buffer strips associated with a cattle feedlot effluent disposal area near Armidale, NSW Australia - ScienceDirect

Search engine	Search string	Document title	URL
Google Scholar	Phosphorus retention buffer strips	Seasonal Efficacy of Vegetated Filter Strips for Phosphorus Reduction in Surface Runoff	Seasonal Efficacy of Vegetated Filter Strips for Phosphorus Reduction in Surface Runoff - Vanrobaeys - 2019 - Journal of Environmental Quality - Wiley Online Library
Google Scholar	Nutrient removal buffer strips	Field assessment of bacteria and nutrient removal by vegetative filter strips Kyle R. Douglas-Mankin, Cairo G. Okoren	Microsoft Word - _43-49_1-IJABE-#282-VFS-5-2-11-OK-edited+by+Wu-Pro (idc-online.com)
Google Scholar	Vegetated riparian buffer strips nutrients	Efficacy of vegetative filter strips (VFS) installed at the edge of feedlot to minimize solids and nutrients from runoff	View of EFFICACY OF VEGETATIVE FILTER STRIPS TO MINIMIZE SOLIDS AND NUTRIENTS FROM FEEDLOT RUNOFF (cigrjournal.org)
Google Scholar	Nutrient removal filter strips	Nutrient and sediment removal by switchgrass and cool-season grass filter strips in Central Iowa, USA	Nutrient and sediment removal by switchgrass and cool-season grass filter strips in Central Iowa, USA | SpringerLink
Google Scholar	Phosphorus removal buffer strips	Phosphorus Removal in Vegetated Filter Strips	Phosphorus Removal in Vegetated Filter Strips - Abu-Zreig - 2003 - Journal of Environmental Quality - Wiley Online Library
Google Scholar	Filter strip width nutrient removal	Filter strip performance and processes for different vegetation, widths, and contaminants	Filter strip performance and processes for different vegetation, widths, and contaminants (unl.edu)

Search engine	Search string	Document title	URL
Google Scholar	Vegetative filter strip nutrient losses	Grass Barrier and Vegetative Filter Strip Effectiveness in Reducing Runoff, Sediment, Nitrogen, and Phosphorus Loss	Grass Barrier and Vegetative Filter Strip Effectiveness in Reducing Runoff, Sediment, Nitrogen, and Phosphorus Loss (usda.gov)
Google Scholar	Nutrient removal in riparian buffers	Sediment and nutrient removal in an established multi-species riparian buffer	Sediment and nutrient removal in an established - ProQuest
Google Scholar	Vegetative filter strip nutrient losses	Vegetative Filter Treatment of Dairy Milkhouse Wastewater	Vegetative Filter Treatment of Dairy Milkhouse Wastewater - Schwer - 1989 - Journal of Environmental Quality - Wiley Online Library
Google Scholar	Nutrient dynamics riparian buffer strip	NUTRIENT DYNAMICS IN AN AGRICULTURAL WATERSHED: OBSERVATIONS ON THE ROLE OF A RIPARIAN FOREST	51-Nutrient-Dynamics-in-an-Agricultural-Watershed.pdf (unioncounty-fl.gov)
Google	Buffer strip nitrogen removal	Nitrate–nitrogen reduction by established tree and pasture buffer strips associated with a cattle feedlot effluent disposal area near Armidale, NSW Australia	Nitrate–nitrogen reduction by established tree and pasture buffer strips associated with a cattle feedlot effluent disposal area near Armidale, NSW Australia - ScienceDirect

Search engine	Search string	Document title	URL
Google	Buffer strip denitrification	Nitrous oxide production and potential denitrification in soils from riparian buffer strips: Influence of earthworms and plant litter	Nitrous oxide production and potential denitrification in soils from riparian buffer strips: Influence of earthworms and plant litter (mcgill.ca)
Jstor	Floodplain ponds N and P assimilation	Nutrient Assimilative Capacity of an Alluvial Floodplain Swamp	Nutrient Assimilative Capacity of an Alluvial Floodplain Swamp on JSTOR
Google	Buffer strips diffuse pollution	Buffers for biomass production in temperate European agriculture: A review and synthesis on function, ecosystem services and implementation	Buffers for biomass production in temperate European agriculture: A review and synthesis on function, ecosystem services and implementation - ScienceDirect
N/A	N/A	Mitigating diffuse water pollution from agriculture: Riparian buffer strip performance with width	(PDF) Mitigating diffuse water pollution from agriculture: Riparian buffer strip performance with width (researchgate.net)
Google	Buffer strips nitrogen	Effect of margin strips on soil mineral nitrogen and plant biodiversity	[PDF] Effect of margin strips on soil mineral nitrogen and plant biodiversity | Semantic Scholar
Google Scholar	Buffer strips nitrogen	Soil nitrogen cycle processes in urban riparian zones	Soil nitrogen cycle processes in urban riparian zones. | Semantic Scholar

Search engine	Search string	Document title	URL
Google Scholar	Nutrient removal buffer zone	Buffer zones: their processes and potential in water protection	Buffer zones: their processes and potential in water protection : Rothamsted Research
Google Scholar	Nutrient removal buffer zone	Buffer zones to improve water quality: a review of their potential use in UK agriculture	Buffer zones to improve water quality: a review of their potential use in UK agriculture - ScienceDirect
Google Scholar	Buffer strip nitrogen removal	Groundwater nitrate removal in riparian buffer zones: a review of research progress in the past 20 years	Groundwater nitrate removal in riparian buffer zones: a review of research progress in the past 20 years | SpringerLink
Google Scholar	buffer area nutrient removal	Water quality management dilemma: Increased nutrient, carbon, and heavy metal exports from forestry-drained peatlands restored for use as wetland buffer	Water quality management dilemma: Increased nutrient, carbon, and heavy metal exports from forestry-drained peatlands restored for use as wetland buffer areas - ScienceDirect
N/A	N/A	Mitigation options for reducing nutrient emissions from agriculture : a study amongst European member states of Cost action 869	Mitigation options for reducing nutrient emissions from agriculture : a study amongst European member states of Cost action 869 | Semantic Scholar
N/A	N/A	3D buffer strips: designed to deliver more for the environment	3D buffer strips: designed to deliver more for the environment - GOV.UK (www.gov.uk)

Search engine	Search string	Document title	URL
Google	Buffer strip nitrogen retention	A Meta-Analysis on Nitrogen Retention by Buffer Zones	[A Meta-Analysis on Nitrogen Retention by Buffer Zones - Valkama - 2019 - Journal of Environmental Quality - Wiley Online Library]()
Jstor	Buffer strip nitrogen retention	Nutrient Retention in Riparian Ecotones	[Nutrient Retention in Riparian Ecotones on JSTOR]()
Google	vegetated buffer strips nutrients	A Review of Vegetated Buffers and a Meta-analysis of Their Mitigation Efficacy in Reducing Nonpoint Source Pollution	[A Review of Vegetated Buffers and a Meta-analysis of Their Mitigation Efficacy in Reducing Nonpoint Source Pollution - Zhang - 2010 - Journal of Environmental Quality - Wiley Online Library]()
DONE	Riparian nutrient retention	Nutrient Retention in Riparian Ecotones	[Nutrient Retention in Riparian Ecotones on JSTOR]()

Table A:4. River channel re-naturalisation metadata (N/A refers to sources which were not found online)

Search engine	Search string	Document title	URL
Google Scholar	River restoration nutrient consequences	A catchment-scale approach to the physical restoration oflowland UK ri7ers	A catchment-scale approach to the physical restoration of lowland UK rivers - Harper - 1999 - Aquatic Conservation: Marine and Freshwater Ecosystems - Wiley Online Library
Google Scholar	River restoration nutrient consequences	Basic Principles and Ecological Consequences of Changing Water Regimes on Nitrogen Cycling in Fluvial Systems	s00267-002-2736-1.pdf (springer.com)
Google Scholar	River restoration nutrient consequences	Assessing stream restoration effectiveness at reducing nitrogen export to downstream waters	Assessing stream restoration effectiveness at reducing nitrogen export to downstream waters - Filoso - 2011 - Ecological Applications - Wiley Online Library
Google Scholar	River restoration nutrient effects	Effects of Channel Restoration on Water Velocity, Transient Storage, and Nutrient Uptake in a Channelized Stream	Effects of Channel Restoration on Water Velocity, Transient Storage, and Nutrient Uptake in a Channelized Stream | Environmental Science & Technology (acs.org)
Google Scholar	Stream restoration nitrogen	Effects Of Stream Restoration On Denitrification In An Urbanizing Watershed	EFFECTS OF STREAM RESTORATION ON DENITRIFICATION IN AN URBANIZING WATERSHED - Kaushal - 2008 - Ecological Applications - Wiley Online Library

Search engine	Search string	Document title	URL
Google Scholar	Straightened river naturalisation N and P	Channel Restoration and Riparian Reforestation Along Wilson Creek: A Demonstration Site	Channel Restoration and Riparian Reforestation Along Wilson Creek: A Demonstration Site (ky.gov)
Jstor	River restoration nutrient retention	Does it make economic sense to restore rivers for their ecosystem services?	Does it make economic sense to restore rivers for their ecosystem services? - Acuña - 2013 - Journal of Applied Ecology - Wiley Online Library
Google	Urban river restoration nitrogen	Influence of urban river restoration on nitrogen dynamics at the sediment-water interface	Influence of urban river restoration on nitrogen dynamics at the sediment-water interface (plos.org)
Google	Floodplain reconnection nitrogen removal	Long-term Assessment of Floodplain Reconnection as a Stream Restoration Approach for Managing Nitrogen in Groundwater and Surface Water	5aa4e4e8-6bfe-4553-8277-00d4e6d99a84.pdf (researchsquare.com)
Google Scholar	Floodplain reconnection nutrient removal	Effectiveness of a newly reconstructed floodplain oxbow to reduce NO3-N loads from a spring flood	Effectiveness of a newly reconstructed floodplain oxbow to reduce NO3-N loads from a spring flood - ScienceDirect

Search engine	Search string	Document title	URL
Google Scholar	Nutrient removal weirs	Effectiveness of low-grade weirs for nutrient removal in an agricultural landscape in the Lower Mississippi Alluvial Valley	Effectiveness of low-grade weirs for nutrient removal in an agricultural landscape in the Lower Mississippi Alluvial Valley - ScienceDirect
Google Scholar	River restoration water quality	River restoration: the fuzzy logic of repairing reaches to reverse catchment scale degradation	River restoration: the fuzzy logic of repairing reaches to reverse catchment scale degradation - Bernhardt - 2011 - Ecological Applications - Wiley Online Library
Google	Hyporheic exchange nitrogen	The hyporheic handbook: groundwater-surface water interface and hyporheic zone for environment managers	The hyporheic handbook: groundwater-surface water interface and hyporheic zone for environment managers - GOV.UK (www.gov.uk)
Google	River restoration nitrogen	Stream restoration strategies for reducing river nitrogen loads	Stream restoration strategies for reducing river nitrogen loads - Craig - 2008 - Frontiers in Ecology and the Environment - Wiley Online Library
Google	River restoration nitrogen	Assessing stream restoration effectiveness at reducing nitrogen export to downstream waters	Assessing stream restoration effectiveness at reducing nitrogen export to downstream waters - PubMed (nih.gov)
Google	Hyporheic exchange nitrogen	Streambed nitrogen cycling beyond the hyporheic zone: Flow controls on horizontal patterns and depth distribution of nitrate and dissolved oxygen in the upwelling groundwater of a lowland river	Streambed nitrogen cycling beyond the hyporheic zone: Flow controls on horizontal patterns and depth distribution of nitrate and dissolved oxygen in the upwelling groundwater of a lowland river - Krause - 2013 - Journal of

Search engine	Search string	Document title	URL
			Geophysical Research: Biogeosciences - Wiley Online Library
Google	River restoration nutrient consequences	What role does stream restoration play in nutrient management?	What role does stream restoration play in nutrient management?: Critical Reviews in Environmental Science and Technology: Vol 47, No 6 (tandfonline.com)
Google	River restoration nutrient consequences	Effects of upland disturbance and instream restoration on hydrodynamics and ammonium uptake in headwater streams	Effects of upland disturbance and instream restoration on hydrodynamics and ammonium uptake in headwater streams | Journal of the North American Benthological Society: Vol 26, No 1 (uchicago.edu)

Table A:5. ELJ research metadata

Search engine	Search string	Document title	URL
Google Scholar	Beaver dam engineering ecosystem benefits	Habitat engineering by beaver benefits aquatic biodiversity and ecosystem processes in agricultural streams	Habitat engineering by beaver benefits aquatic biodiversity and ecosystem processes in agricultural streams - Law - 2016 - Freshwater Biology - Wiley Online Library
Google Scholar	Beaver dam engineering nutrient pollution	Eurasian beaver activity increases water storage, attenuates flow and mitigates diffuse pollution from intensively managed grasslands	Eurasian beaver activity increases water storage, attenuates flow and mitigates diffuse pollution from intensively-managed grasslands - ScienceDirect
Google Scholar	Beaver ponds nutrient effects	Beaver pond biogeochemical effects in the Maryland Coastal Plain	Beaver pond biogeochemical effects in the Maryland Coastal Plain
Google Scholar	Beaver ponds nutrient effects	The Effect of Beaver Ponds on Water Quality in Rural Coastal Plain Streams	(PDF) The Effect of Beaver Ponds on Water Quality in Rural Coastal Plain Streams (researchgate.net)
Google	Beaver water quality impacts	Riparian wetland rehabilitation and beaver re-colonization impacts on hydrological processes and water quality in a lowland agricultural catchment	Riparian wetland rehabilitation and beaver re-colonization impacts on hydrological processes and water quality in a lowland agricultural catchment - ScienceDirect

Search engine	Search string	Document title	URL
Google	Beaver water quality impacts	Beaver: Nature's ecosystem engineers	Beaver: Nature's ecosystem engineers - Brazier - 2021 - WIREs Water - Wiley Online Library
Google	Beaver dam water quality	The geomorphic influences of beaver dams and failures of beaver dams	The geomorphic influences of beaver dams and failures of beaver dams - ScienceDirect
Google	Beaver dam water quality	Meta-analysis of environmental effects of beaver in relation to artificial dams	Meta-analysis of environmental effects of beaver in relation to artificial dams - IOPscience
Google	Leaky dam water quality	Leaky dams	https://www.edenriverstrust.org.uk/your-eden/explore-edens-rivers/leaky-dams/
Google	Woody debris introduction nutrients	Restoration of wood loading has mixed effects on water, nutrient, and leaf retention in Basque mountain streams	Restoration of wood loading has mixed effects on water, nutrient, and leaf retention in Basque mountain streams | Freshwater Science: Vol 35, No 1 (uchicago.edu)
Google	Organic debris river nutrients	N processing within geomorphic structures in urban streams	N processing within geomorphic structures in urban streams | Journal of the North American Benthological Society: Vol 24, No 3 (uchicago.edu)
Google	Organic debris river nutrients	Microbial biomass and activity in geomorphic features in forested and urban restored and degraded streams	Microbial biomass and activity in geomorphic features in forested and urban restored and degraded streams - ScienceDirect

Search engine	Search string	Document title	URL
Google	Beaver water quality impacts	Habitat engineering by beaver benefits aquatic biodiversity and ecosystem processes in agricultural streams	Habitat engineering by beaver benefits aquatic biodiversity and ecosystem processes in agricultural streams - Law - 2016 - Freshwater Biology - Wiley Online Library
Google	Beaver ponds nitrogen	Beaver Ponds: Resurgent Nitrogen Sinks for Rural Watersheds in the Northeastern United States	Beaver Ponds: Resurgent Nitrogen Sinks for Rural Watersheds in the Northeastern United States - Lazar - 2015 - Journal of Environmental Quality - Wiley Online Library
Google	Beaver dam sediment	Beaver dams and channel sediment dynamics on Odell Creek, Centennial Valley, Montana, USA	Beaver dams and channel sediment dynamics on Odell Creek, Centennial Valley, Montana, USA - ScienceDirect
Google	Beaver dam sediment	Beaver as Engineers: Influences on Biotic and Abiotic Characteristics of Drainage Basins	Beaver as Engineers: Influences on Biotic and Abiotic Characteristics of Drainage Basins | SpringerLink
Google	Beaver wetland sediment	Sediment and nutrient storage in a beaver engineered wetland	Sediment and nutrient storage in a beaver engineered wetland - Puttock - 2018 - Earth Surface Processes and Landforms - Wiley Online Library
Google	Woody debris introduction nutrients	Effects of Large Woody Debris Addition on Stream Habitat and Brook Trout Populations in Appalachian Streams	Effects of Large Woody Debris Addition on Stream Habitat and Brook Trout Populations in Appalachian Streams | SpringerLink

Search engine	Search string	Document title	URL
Google	Beaver re-colonisation water quality	Riparian wetland rehabilitation and beaver re-colonization impacts on hydrological processes and water quality in a lowland agricultural catchment	[Riparian wetland rehabilitation and beaver re-colonization impacts on hydrological processes and water quality in a lowland agricultural catchment - ScienceDirect]()

Table A:6. Agroforestry research metadata (N/A refers to sources which were not found online)

Search engine	Search string	Document title	URL
Google Scholar	Agroforestry nutrient reductions	Agroforestry as an Approach to Minimizing Nutrient Loss From Heavily Fertilized Soils: The Florida Experience	[(PDF) Agroforestry as an Approach to Minimizing Nutrient Loss From Heavily Fertilized Soils: The Florida Experience (researchgate.net)]()
Google Scholar	Silvopasture phosporus loss reductions	Silvopasture for reducing phosphorus loss from subtropical sandy soils	[Silvopasture for reducing phosphorus loss from subtropical sandy soils | SpringerLink]()
Google Scholar	Agroforestry inercropping nutrient losses	Response of Nutrients and Sediment to Hydrologic Variables in Switchgrass Intercropped Pine Forest Ecosystems on Poorly Drained Soil	[Response of Nutrients and Sediment to Hydrologic Variables in Switchgrass Intercropped Pine Forest Ecosystems on Poorly Drained Soil (usda.gov)]()

Search engine	Search string	Document title	URL
Google Scholar	Agroforestry intercropping nutrient losses	Analysis of Nitrogen and Phosphorus Input and Output Characteristics and Use Efficiency in Pear Tree–Upland Rice Intercropping Systems	Analysis of Nitrogen and Phosphorus Input and Output Characteristics and Use Efficiency in Pear Tree–Upland Rice Intercropping Systems: Journal of Plant Nutrition: Vol 28, No 12 (tandfonline.com)
Google Scholar	Agroforestry intercropping nitrogen and phosphorus losses	Reducing nitrogen and phosphorus losses from arable slope land with contour hedgerows and perennial alfalfa mulching in Three Gorges Area, China	Reducing nitrogen and phosphorus losses from arable slope land with contour hedgerows and perennial alfalfa mulching in Three Gorges Area, China - ScienceDirect
Google Scholar	Agroforestry intercropping nutrient uptake	Tree uptake of excess nutrients and herbicides in a maize-olive tree cultivation system	Tree uptake of excess nutrients and herbicides in a maize-olive tree cultivation system: Journal of Environmental Science and Health, Part A: Vol 53, No 1 (tandfonline.com)
Google Scholar	Alley cropping nutrient losses	Reduced nitrogen losses after conversion of row crop agriculture to alley cropping with mixed fruit and nut trees	Reduced nitrogen losses after conversion of row crop agriculture to alley cropping with mixed fruit and nut trees - ScienceDirect
Google Scholar	Agroforestry intercropping nitrates	Nitrate and Escherichia coli NAR analysis in tile drain effluent from a mixed tree intercrop and monocrop system	Nitrate and Escherichia coli NAR analysis in tile drain effluent from a mixed tree intercrop and monocrop system - ScienceDirect

Search engine	Search string	Document title	URL
Google Scholar	Agroforestry alley cropping nutrient losses	Effects of alley crop planting on soil and nutrient losses in the citrus orchards of the Three Gorges Region	Effects of alley crop planting on soil and nutrient losses in the citrus orchards of the Three Gorges Region - ScienceDirect
Google Scholar	Silvopasture nitrate leaching	Soil nitrate leaching in silvopastures compared with open pasture and pine plantation	Soil nitrate leaching in silvopastures compared with open pasture and pine plantation. | Semantic Scholar
Google	Agroforestry for nutrient retention	Agroforestry Practices for Improving Soil Nutrient Status	(PDF) Agroforestry Practices for Improving Soil Nutrient Status (researchgate.net)
Google	Agroforestry for nutrient retention	Agroforestry Trees for Nutrient Cycling and Sustainable Management	Agroforestry Trees for Nutrient Cycling and Sustainable Management: East African Agricultural and Forestry Journal: Vol 62, No 1-2 (tandfonline.com)
Google Scholar	Nitrogen retention agroforestry	Agroforestry and Opportunities for Improved Nitrogen Management	Agroforestry and Opportunities for Improved Nitrogen Management | SpringerLink
Google	Short rotation coppice nutrient removal	Short rotation coppice establishment	Short rotation coppice establishment - Forest Research

Search engine	Search string	Document title	URL
Google Scholar	Silvopasture nitrate leaching	The potential for poplar and willow silvopastoral systems to mitigate nitrate leaching from intensive agriculture in New Zealand	[PDF] The potential for poplar and willow silvopastoral systems to mitigate nitrate leaching from intensive agriculture in New Zealand | Semantic Scholar
Google Scholar	tree nutrient uptale	Nutrient and water uptake by roots of forest trees	Nutrient and water uptake by roots of forest trees - George - 1996 - Zeitschrift für Pflanzenernährung und Bodenkunde - Wiley Online Library
Google Scholar	Short rotation coppice nutrient removal	Carbon and nutrient dynamics in short-rotation coppice of poplar and willow in a converted marginal land, a case study in central France	Carbon and nutrient dynamics in short-rotation coppice of poplar and willow in a converted marginal land, a case study in central France | SpringerLink
Google	Agriculture phosphorus	Phosphorus in Agriculture and in Relation to Water Quality	Phosphorus in Agriculture and in Relation to Water Quality (nutrientmanagement.org)
Google	Nutrient removal rates fruit	Fruit mineral removal rates from New Zealand apple (Malus domestica) orchards in the Nelson region	Fruit mineral removal rates from New Zealand apple (Malus domestica) orchards in the Nelson region: New Zealand Journal of Crop and Horticultural Science: Vol 34, No 1 (tandfonline.com)
Google	Agriculture phosphorus	Phosphorus plant removal from European agricultural land	Phosphorus plant removal from European agricultural land | SpringerLink

Search engine	Search string	Document title	URL
N/A	N/A	The agroforestry handbook	the-agroforestry-handbook.pdf (soilassociation.org)
Google	Mixed tree nutrient removal	The influence of mixed tree plantations on the nutrition of individual species: a review	The influence of mixed tree plantations on the nutrition of individual species: a review - PubMed (nih.gov)
Google	Orchards nutrient removal	Orchards	Orchards - British Habitats - Woodland Trust
N/A	N/A	Agroforestry: A New Approach to increasing farm production	Agroforestry - a new approach to increasing farm production | Nuffield Farming Scholarships (nuffieldscholar.org)
N/A	N/A	Environmental effects of densely planted willow and poplar in a silvopastural system	(PDF) Pasture production under densely planted young willow and poplar in a silvopastoral system (researchgate.net)
N/A	N/A	Leaching CABI book: Chapter 7 Nutrient Leaching	Nutrient leaching. | Trees, crops and soil fertility: concepts and research methods (cabidigitallibrary.org)
N/A	N/A	Silvopasture for reducing phosphorus loss from subtropical sandy soils	Silvopasture for reducing phosphorus loss from subtropical sandy soils | SpringerLink

Search engine	Search string	Document title	URL
N/A	N/A	Safety-net role of tree roots: evidence from a pecan - cotton alley cropping system in the southern united states	Safety-net role of tree roots: evidence from a pecan (Carya illinoensis K. Koch)–cotton (Gossypium hirsutum L.) alley cropping system in the southern United States - ScienceDirect
N/A	N/A	The impact of rural land management changes on soil hydraulic properties and runoff processes: results from experimental plots in upland UK	The impact of rural land management changes on soil hydraulic properties and runoff processes: results from experimental plots in upland UK - Marshall - 2014 - Hydrological Processes - Wiley Online Library
N/A	N/A	The Potential for Poplar and Willow Silvopastoral Systems to Mitigate Nitrate Leaching from Intensive Agriculture in New Zealand	[PDF] The potential for poplar and willow silvopastoral systems to mitigate nitrate leaching from intensive agriculture in New Zealand | Semantic Scholar
N/A	N/A	Reducing nutrient loss from farms through silvopastoral practices in coarse-textured soils of Florida USA	Reducing nutrient loss from farms through silvopastoral practices in coarse-textured soils of Florida, USA - ScienceDirect
N/A	N/A	Soil Nitrate Leaching in Silvopastures Compared with Open Pasture and Pine Plantation	Soil nitrate leaching in silvopastures compared with open pasture and pine plantation. (cabdirect.org)
N/A	N/A	Silvopasture (Word doc)	N/A

Appendix 2: UKCEH Habitat Classes

LCM2015 class	Brief Review
Broadleaved woodland	Broadleaved woodlands are characterised by stands >5 m high with tree cover >20%; scrub (<5 m) requires cover >30% for inclusion in this BH. Such fine distinctions cannot be made through remote sensing. Open-canopy woodland (stands with trees <50%) is a particular problem, albeit occurring relatively rarely, and may not often be mapped consistently, due to the dominance of the non-woodland plants. Stands with near-closed canopies can be interpreted easily in the field and pure examples can normally be found for training the classifier. Broadleaved evergreen trees (part of this BH) rarely occur in stands >1ha (an area large enough to create suitable training areas appropriate for classification). Mixed woodland (see differences from LCM2007 section). Where individual stands of broad-leaved or evergreen trees exceeded the minimum mappable unit, they were treated as separate blocks within the woodland; in many parts of the UK, truly 'mixed woodlands' as opposed to those with mosaic-blocks of broadleaved and coniferous trees, are unusual.
'Coniferous Woodland'	'*Coniferous Woodland'* includes semi-natural stands and plantations, with cover >20%. The recognition of coniferous woodland is generally straightforward. Rare examples of open canopy semi-natural pinewoods may have been classified according to the dominant understorey class. The BH includes new plantation and recently felled areas (this is a class where the BH definition is based on land use, i.e. forestry, rather than cover). New plantations, predominantly heather and/or grass, for example, are recorded as such by the spectral classification of image data. New plantations are only consistently recorded as conifers when tree cover is sufficient to strongly influence the reflectance. LCM2015 includes newly felled areas. Once they are fully

LCM2015 class	Brief Review
	recolonised by rough grass, heath or scrub, they are recorded according to that cover. Deciduous larch is discernible from other deciduous trees and is generally correctly included with other conifers.
‘Arable and Horticulture’	This Broad Habitat includes annual crops, perennial crops such as berries and orchards and freshly ploughed land. Orchards with a ground flora are hard to distinguish.
‘Improved Grassland’	Improved grassland is distinguished from semi-natural grasslands based on its higher productivity, lack of winter senescence and location and/or context. In some cases heavy grazing can cause mis-classification with, arable land or semi-natural grassland. Some confusion occurs between ‘*Improved Grassland’* and ‘*Calcareous Grassland’* and ‘*Neutral Grassland’*, as ‘*Calcareous Grassland’* and ‘*Neutral Grassland’* are often very productive grassland and so spectrally very similar to ‘*Improved Grassland*’.
‘Neutral Grassland’	For LCM2015 ‘*Neutral Grassland’* is mapped spectrally, however, the inclusion of ancillary layers for slope and distance to rivers is expected to improve the classification of ‘*Neutral Grassland*’ on flood plains. Areas identified as ‘*Neutral Grassland’* by LCM should probably be treated as having the potential to be ‘Neutral grassland’ as for a conclusive classification field survey is required to make a determination based on botanical composition. ‘*Neutral Grassland’* also includes semi-improved grasslands managed for silage, hay or pasture (Jackson, 2000), which in LCM2015 will often be classified as ‘*Improved Grassland’*.
‘Calcareous Grassland’	For LCM2015 ‘*Calcareous Grassland’* is mapped spectrally, however, the inclusion of ancillary layers for slope is expected to improve the classification of ‘*Calcareous Grassland’* in some cases. Areas identified as ‘*Calcareous Grassland*’ by LCM should probably be treated as having the potential to be ‘*Calcareous*

LCM2015 class	Brief Review
	Grassland' as for a conclusive classification field survey is required to make a determination based on botanical composition.
'Acid Grassland'	For LCM2015, '*Acid Grassland'* is mapped spectrally. Bracken can be mapped using LCM2015 methods, but it depends on image timing and suitable training areas (bracken often fails to offer stands sufficiently extensive for classification and training), so for consistency it is assigned to '*Acid Grassland'*. However, some stands of bracken can be identified at the subclass level.
Note about grassland classes	The comparisons between previous LCM data and other data sets (for example the ground reference polygons and Countryside Survey in 2007 Broad Habitat maps) (Morton *and others,* 2011), have shown that '*Neutral Grassland'* and '*Calcareous Grassland'* were often mis-classified as '*Improved Grassland'*. Some users may wish to aggregate the grassland classes together, if this is appropriate for their needs.
'Heather' and 'Heather grassland' **(Together form the** **'Dwarf Shrub Heath' Broad Habitat)**	*'Dwarf Shrub Heath'* is divided into two classes, depending on the density of Heather, producing 'Heather' and 'Heather grassland' classes respectively. This is similar to LCM1990's and LCM2000s Open and Dense Shrub Heath classes. Note: the Land Cover Maps typically show confusion over the separation of '*Bog*' and '*Dwarf Shrub Heath'*, however, this only affects the separation of these two BHs and they are often difficult to separate in the field. Note, the Broad Habitat classification treats ericaceous vegetation on peat > 0.5 m depth as '*Bog*'.
'Fen, Marsh and Swamp'	'*Fen, Marsh and Swamp'* includes fen, fen meadows, rush pasture, swamp, flushes and springs. From a remote sensing perspective '*Fen, Marsh and Swamp'* is problematic as it is can be comprised of a wide range of land cover types and many patches of Fen are below the LCM2015 MMU. The small size of '*Fen, Marsh and*

LCM2015 class	Brief Review
	Swamp' patches, plus their typically mosaic nature make it difficult to find representative areas of sufficient size to conduct a spectral classification. Consequently, 'Fen, Marsh and Swamp' will be underestimated by LCM2015.
'Bog'	*'Bog'* includes ericaceous, herbaceous and mossy swards in areas with a peat depth > 0.5 m. 'Bog' forms part of an ecological continuum covering 'Acid Grassland', 'Dwarf Shrub Heath' and some types of 'Fen, Marsh and Swamp' and the separation of these habitats can be difficult, as the surface vegetation (i.e. land cover) maybe very similar and the division rests on the depth of peat. The division in the field can account for species presence, plus peat depth, but for LCM2015 the division is based on the spectral data and presumably also the slope data.
Saltwater	Saltwater is mapped to a limited extent around the coastline of the UK. The extent is constrained by the extent of the digital cartography, which covers land and tidal areas, but not sea.
Freshwater	This is based on merging two freshwater BHs ('*Standing Open Water and Canals'* and '*Rivers and Streams'*), as they cannot be reliably separated from each other using the methods and data used for LCM2015. In many cases small and/or narrow water bodies fall below the MMU. Water bodies > 0.5 ha are readily mapped, as are very wide rivers (>50 m). The main exceptions are temporary water bodies, especially in quarries where the water body extent differs between the two images and differs from the associated polygon shape. Water in some quarries is strongly affected by the minerals in the rock and can result in strange water colours that maybe misclassified.
'Inland Rock'	This Broad Habitat type covers both natural and artificial exposed rock surfaces which are >0.25ha, such as inland cliffs, caves, screes and limestone pavements, as well as various forms of excavations and waste tips such as quarries and quarry waste. To be classified as '*Inland*

LCM2015 class	Brief Review
	Rock' the rock has to be the dominant spectral signature.
'Urban' and 'Suburban' **(together form the 'Built-up Areas and Gardens' Broad Habitat)**	Within the '*Built-up Areas and Gardens'* Broad Habitat LCM2015 recognises two categories that can be determined reliably: 'Urban' and 'Suburban'. 'Urban' includes dense urban, such as town and city centres, where there is typically little vegetation. 'Urban' also includes areas such as dock sides, car parks and industrial estates. 'Suburban' includes suburban areas where the spectral signature is a mix of urban and vegetation signatures.
'Supra-littoral Rock'	Features that may be present in this coastal class include vertical rock, boulders, gullies, ledges and pools. Very limited areas are mappable using satellite remote sensing.
'Supra- **littoral Sediment'**	This class includes sand-dunes, which are reliably mapped in this class. Areas of coastal sand may be confused between this class and the 'Littoral sediment' class.
'Supra- **littoral Sediment'**	This class includes sand-dunes, which are reliably mapped in this class. Areas of coastal sand may be confused between this class and the 'Littoral sediment' class.
'Littoral Rock'	These classes are those in the maritime zone on a rocky coastline. They are generally more extensive than supra-littoral rock and thus more readily mappable from satellite images.
'Littoral sediment' and 'Saltmarsh' **(Together form the 'Littoral Sediment' Broad Habitat)**	Littoral sediment is mapped as two classes: 'Saltmarsh' and 'Littoral sediment'. Saltmarsh is a Priority Habitat and of sufficient extent and spectral distinction to be mapped consistently. The remaining 'Littoral Sediment' is mapped spectrally, although there may be some confusion with the 'Supra-littoral sediment' class.

Appendix 3: Non robust data for N and P removal efficiencies

Table C:1. Mean reduction values for N from different studies without robust methodologies implementing different forms of river restoration techniques. Negative percentage reductions show schemes that resulted in an increase in N.

Study	Form of RR	Location	Form of N	Mean reduction (%)	Conc. or load?	Reason for rejection
Lavelle and others, (2019)	Re-meandering	UK	NO3	0.8	Conc.	Sampled for 3 months
Lavelle and others, (2019)	Implementation of berms and redirecting channel flow	UK	NO3	-3.2	Conc.	Sampled for 3 months
Lavelle and others, (2019)	Weir lowering and shortening of fish passages	UK	NO3	10.2	Conc.	Sampled for 3 months
Lavelle and others, (2019)	Weir removal, channel narrowing and implementation of pool and riffle sequences	UK	NO3	2.6	Conc.	Sampled for 3 months
Lavelle and others, (2019)	Re-meandering and backwater creation	UK	NO3	0	Conc.	Sampled for 3 months
Bukaveckas and others, (2007)	Floodplain reconnection and	NE USA	NO3	-21.6	Conc.	Monitoring only April – June

Study	Form of RR	Location	Form of N	Mean reduction (%)	Conc. or load?	Reason for rejection
	implementation of pool and riffle sequences					
Ren and others, (2015)	Constructed wetlands beside the river to treat flooded channel flow and wastewater	China	NO3 TN	43.4 67.5	Conc.	Sampling not carried out continuously for 1 year
Ren and others, (2015)	Constructed wetlands beside the river to treat flooded channel flow and wastewater	China	NO3 TN	24.5 71.0	Conc.	Sampling not carried out continuously for 1 year
Ren and others, (2015)	Engineered shallow aquifer infiltration system	China	NO3 TN	38.1 74.1	Conc.	Sampling not carried out continuously for 1 year
Ren and others, (2015)	Planting of submerged vegetation	China	NO3 TN	38.5 71.1	Conc.	Sampling not carried out continuously for 1 year

Table C:2. Mean reduction values for P studies without robust methodologies implementing different forms of river restoration techniques. Negative percentage shows the scheme resulted in an increase in P.

Study	Form of RR	Location	Form of P	Mean reduction (%)	Conc. or load	Reason for rejection
Bukaveckas (2007)	Floodplain reconnection and implementation of pool and riffle sequences	NE USA	SRP	33.3	Conc.	Only surveyed April – June so seasonality was not considered, only 44 samples.

Table C:3. Mean reduction values for N from different studies without robust methodologies for removal by beaver dams.

Study	Type of dam	Location	Form of N	Mean reduction (%)	Conc. or load	Reason for rejection
Bason and others, (2017)	North American beaver dam	North Carolina USA	Nitrate	19.0	Conc.	Sampled for 5 months

Table C:4. Mean reduction values for P from non-robust studies looking at silvopasture agroforestry

Study	Type of silvopasture	Location	Form of P	Mean reduction (%)	Conc. or load	Reason for rejection
Nair and others, (2007)	Silvopasture with 494 trees/ha	Florida, USA	WSP	54.2	Conc.	Monitoring for only 2-3 days

Study	Type of silvopasture	Location	Form of P	Mean reduction (%)	Conc. or load	Reason for rejection
Nair and others, (2007)	Silvopasture with 309 trees/ha	Florida, USA	WSP	84.0	Conc.	Monitoring for only 2-3 days
Michel and others, (2007)	Bahiagrass, slash pine and livestock	Florida, USA	WSP	48.6	Conc.	Monitoring for only one day
Michel and others, (2007)	Bahiagrass, slash pine and livestock	Florida, USA	WSP	59.4	Conc.	Monitoring for only one day
Michel and others, (2007)	Bahiagrass, slash pine and livestock	Florida, USA	WSP	51.3	Conc.	Monitoring for only one day
Michel and others, (2007)	Bahiagrass, slash pine and livestock	Florida, USA	WSP	38.2	Conc.	Monitoring for only one day

Table C:5. Mean reduction values for N from non-robust studies looking at silvopasture agroforestry

Study	Type of silvopasture	Location	Form of N	Mean reduction (%)	Conc. or load	Reason for rejection
Nair and others, (2007)	Silvopasture with 494 trees/ha	Florida, USA	Nitrate	20.1	Conc.	Sampled for 2 – 3 days

Study	Type of silvopasture	Location	Form of N	Mean reduction (%)	Conc. or load	Reason for rejection
Nair and others, (2007)	Silvopasture with 309 trees/ha	Florida, USA	Nitrate	21.3	Conc.	Sampled for 2 – 3 days

Table C:6. Mean reduction values for N from non-robust studies looking at silvo-arable agroforestry

Study	Type of silvo-arable	Location	Form of N	Mean reduction (%)	Conc or load	Reason for rejection
Pavlidis and others, (2017)	Olive trees and maize	Greece	Nitrate	75.6	Conc.	Monitoring for 6 months only
Dougherty and others, (2009)	Wheat and multiple tree species	Ontario, Canada	Nitrate	4.6	load	Monitoring 3x weekly for 8 months
Dougherty and others, (2009)	Corn and multiple tree species	Ontario, Canada	Nitrate	46.2	load	Monitoring 5x daily for 8 months

Table C:7. Mean reduction values for P from non-robust studies looking at silvo-arable agroforestry

Study	Type of silvo-arable	Location	Form of P	Mean reduction (%)	Conc. or load	Reason for rejection
Pavlidis and others, (2017)	Olive trees and maize	Greece	Phosphate	100.0	Conc.	Monitoring for only 6 months

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