CENTRE OF EXPERTISE FOR WATERS

# Prioritising Research and Development Gap Opportunities for River Woodlands

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# List of commonly used abbreviations

| | |
|---|---|
| **DOC** | Dissolved Organic Carbon |
| **FGS** | Forestry Grant Scheme |
| **FIRNS** | Facility for Investment Readiness Scotland |
| **GHG** | Greenhouse Gas |
| **GHP** | Green Health Partnerships |
| **LWS** | Large Woody Structure |
| **NEB** | Natural Environment Bill |
| **NPF4** | National Planning Framework 4 |
| **NRF** | Nature Restoration Fund |
| **ONHS** | Scotland's Our Natural Health Service |
| **RBMP** | River Basin Management Plan |
| **R&D** | Research and Development |
| **RW** | River Woodlands |
| **SBAG** | Scottish Beaver Advisory Group |
| **SBS** | Scottish Biodiversity Strategy |
| **SNFRS** | Scottish National Flood Resilience Strategy |
| **SFS** | Scotland's Forestry Strategy 2019 – 2029 |
| **SNAP3** | Scottish National Adaptation Plan 3 |
| **SRDP** | Scottish Rural Development Programme |
| **STLUS** | Scottish Third Land Use Strategy |
| **SWT** | Scottish Wildlife Trust |
| **TNFD** | Taskforce on Nature related Financial Disclosures |
| **WCC** | Woodland Carbon Code |
| **WFD** | Water Framework Directive |
| **WWC** | Woodland Water Code |

# Glossary

**Drought**: We use the term 'drought' as shorthand for short-term water stress related to a temporary imbalance between water demand and supply, as well as for longer-term prolonged period of abnormally dry weather and water scarcity.

**Floodplain**: The area along a river or stream that is subject to natural flooding.

**Gorge**: A deep, narrow river valley with steep slopes.

**River Woodland**: Trees, woodlands and forests, either natural or planted, around the bank and a alongside a natural body of freshwater (especially a stream or river but also including lochs).

**River Woodland Restoration**: The re-establishment of natural river processes, habitats and features by new planting, or regeneration, of the appropriate tree species mixtures matched to location characteristics, designed to bring ecosystem benefits.

**Riparian Zone**: A landscape unit subject to multidirectional fluxes between river systems and uplands, driven by natural and social processes. This crucial interface between terrestrial and aquatic ecosystems extends from the banks by varying distances according to soil, moisture, vegetation that is often distinct from hillslopes and dependant on geoclimatic setting, stream scale and dynamics (Dufour & Rodriguez-Gonzalez, 2019).

# Executive Summary

## Highlights

- River restoration by river woodlands (RW) is becoming commonly applied as a response to challenges for climate resilience, conserving habitats, water and soil quality and wider environmental and community benefits. Whilst scientific knowledge can be assembled from around the world, some processes are less understood and relevance to Scottish conditions varies amongst studies. An earlier report in 2022 evaluated the benefits and states of evidence. Building on this, we review stakeholder prioritisation against evidence status and readiness to inform policy and practice, seeking to maximise opportunities for RW implementation across sectors and Scotland's environment.
- Extensive engagement with 115 stakeholders through a year-long, Scotland 'river woodland conversation' into evidence needs and priorities.
- Review of 60 detailed knowledge gaps across potential RW benefits gives the basis of evidence towards RW implementation.
- Stakeholders support RW benefits but highlight challenges like funding, policy complexities, landowner engagement, and knowledge sharing in turning research into practice.
- Weak evidence exists for key research areas, including RW placement for low river flows, drought-resilient tree species, greenhouse gas (GHG) interactions, and community/social acceptance of river woodland restoration.
- Strong scientific evidence supports RW benefits for clean water, soil quality, biodiversity, herbivore interactions, and species protection, but stakeholders require better knowledge access and guidance.
- More cross-benefit research is needed on RW management, tree placement, effectiveness over time and space, and catchment-scale monitoring and modelling.
- Knowledge synthesis and application outweigh new research needs, with calls for funding solutions, coordinated monitoring, interdisciplinary collaboration, and better communication tools for RW implementation.

## Background and research purpose

River woodlands (RW) play a vital role in supporting healthy rivers, biodiversity, and surrounding ecosystems. When present and in good condition, they can provide benefits such as flood risk alleviation, carbon storage, pollution reduction, resilience to climate change, as well as health and community benefits. Yet, morphological surveys reveal generally poor condition of bankside vegetation, including woodland, in ~55% of the linear bank lengths of Scotland's national surveillance baseline river network (catchments >10km$^2$) (Ogilvy *et al*., 2022). Restoration efforts, supported by projects such as Riverwoods, have gained momentum but challenges remain to scaling up RW restoration. Multiple policies linking to the creation and restoration of RW show the potential widespread benefits (notably: the Scottish Biodiversity Strategy (SBS), Scotland's Forestry Strategy (SFS), Scotland's National Flood Resilience Strategy, Scottish Third Land Use Strategy (STLUS), the Scottish Soils and Water Framework Directives, the recent Scottish National Adaptation Plan 3 (SNAP3), and upcoming Natural Environment Bill). Translating evidence into good practice is a challenge that hinders the development and delivery of policy as well as business involvement and long term-investment.

An earlier review undertaken by Riverwoods (hereby termed the 2022 review) assessed using mixed literature approaches and expert input to classify evidence strength amongst areas of potential RW benefits, but did not consider needs and priorities of stakeholder groups. This project explored interactions between (i) current scientific literature evidence and ongoing knowledge strategies (e.g. monitoring) and (ii) perceptions and needs around evidence from national stakeholders (public, private, third sectors, business, policy and nature finance). The 2022 review concluded ~51 specific knowledge gap statements that underpin three key objectives of this project:

1. To provide an updated scientific literature assessment of the evidence for RW benefits, focussing on the specific gaps considered in the 2022 review as important to knowledge and implementation in Scotland and also newly proposed knowledge gaps from stakeholders;
2. To engage with a wide range of stakeholders from academia, and public, private and third sectors (including policy, nature finance and business representation) across Scotland to identify additional evidence gaps across benefit areas and prioritise evidence needs promoting improved establishment and management of healthy and resilient RW systems;
3. to identify opportunities and mechanisms to address these gaps to enable investment in new and extended RW, and improved/restored river environments.

## Methods

The evidence review assessed global literature (2014-24) using keyword searches on specified (by the 2022 review) and newly identified (as identified by stakeholders) gaps, screening larger numbers of publications to a top five per gap, where possible, and recording metadata (study type, robustness and relevance) into a database. An additional 113 publications (not considered in the 2022 review), resulting in none to five per gap, were used to assess the evidence on the specific gaps (aligned to the stakeholder prioritisation of evidence gaps).

Stakeholder consultation stages comprised: a survey (>150 directly invited, 66 responded) where respondents were introduced to the shortened knowledge gap statements and asked to rank them, identify challenges and propose new gaps; an in-person workshop (15 attendees) that prioritised and discussed gap nuances; one-to-one interviews (n=13) that sought sector representations that were unbalanced in other methods, with semi-structured interviews to go beyond the gap statement focus of earlier stages; two focus groups on policy (n=23) and monitoring (n=9), as well as a consultation on diversifying funding (n=8) to explore topic details with specialists. This achieved a participation balance between academic, private, public and third sector of 21%, 20%, 31% and 28%, respectively. Prioritisation of the evidence gaps emerged from the ranking undertaken during the survey and the workshop. These priorities were then refined by including the priorities raised in the interviews, focus groups and consultation.

The synthesis of the updated evidence review and stakeholder engagement enabled the needs and priorities in relation to available evidence to be analysed. Using a matrix categorising overall cross-sectoral priorities (low to high) by evidence level (weak to strong), it was possible to identify which benefit areas are (i) high priority for more research and knowledge exchange (weak evidence and high stakeholder priority) (ii) high priority for better knowledge exchange and guidance, but not research (strong evidence but high stakeholder priority), and (iii) low to intermediate priority for research and communication. In addition, sector-specific needs, policy demands (based on focus groups and policy document screening), and potential action pathways informed by focus group discussions and consultations were assessed.

## Key findings

- An analysis of global literature addressed 27 potential environmental and societal benefit outcomes (via 51 specific evidence gap statements from the 2022 review) and 9 additional statements (new stakeholder input). We confirmed the 2022 review evidence strength classifications but also downgraded (to moderate) eight cases where previously strong evidence classification was countered by multiple specific gaps which remain unaddressed for topics considered important to RW implementation in Scotland.
- Overall stakeholders understand and show support for multiple benefits of RW. Collectively, they have widely varying needs for, views on, and understanding of, evidence. Generally, they call for integration of evidence and adapted tools across benefit areas rather than a focus on single benefit-topic evidence needs. Our consultations show that strength of evidence must be considered alongside wider societal challenges limiting RW research into practice, such as a lack of funding, incentives, and resources, practical and policy complexities in a context of environmental change, lack of landowner involvement, and a need for collaboration and knowledge sharing.
- Highly prioritised topics across sectors with weak evidence bring clear research needs, namely: RW placement addressing low river flows and tree species and management with respect to drought resilience; GHG emissions interactions with carbon storage and RW land

change; understanding community, policy and social RW preferences and acceptance of RW restoration management.

- In contrast, highly prioritised topics concerning clean water (sediment sources), soil quality (soil loss interdisciplinary issues), biodiversity, herbivore interactions, protection of key species and RW vegetation and space required for morphological outcomes were considered strongly evidenced scientifically. Yet, stakeholder prioritisation included requirements for knowledge availability and good practice guidance.
- There is a need for more cross-benefit topic evidence on RW management, tree placement, the spatial and temporal scales of effectiveness, supported by river-type monitoring strategies and modelling, for example, recording and predicting intervention progress towards achieving multiple benefits and trade-offs at catchment scale.
- Stakeholders reported that new primary knowledge creation needs are outweighed in many aspects by knowledge synthesis and practical application challenges. To enhance and expand RW restoration, efforts must focus on addressing funding gaps, building primary data through controlled experiments, and improving coordinated monitoring, including using structured citizen science alongside traditional study. Resolving data consistency issues, nationally collating datasets, and fostering interdisciplinary knowledge exchange will support the development of robust models, practitioner-targeted communication, and iterative guidance tools to drive effective implementation.

## Recommendations summary

For this project, we developed a series of recommendations to address critical evidence gaps, aimed at enhancing confidence in RW placement, design, and management. By strengthening the underlying evidence base focusing on stakeholders priorities, these recommendations seek to maximise the benefits of RW and minimise unintended consequences. They identify key opportunities for more evidence to increase confidence and enable greater investment in new and expanded RW, and to support improved and restored river environments. The recommendations focus on advancing research and tool development, enhancing long-term monitoring, promoting coordination and knowledge sharing, aligning policy targets, and diversifying funding models. Please see report section 4.6 for full recommendations.

**Strengthen research and tools**: Expand inter-disciplinary studies on RW targeting, management, and monitoring methods; develop screening tools to optimise tree placement and assess ecosystem services.

**Enhance monitoring**: Establish long-term monitoring programs, support citizen science initiatives to improve data collection and engagement, and implement advanced techniques like eDNA and water quality sensor networks.

**Promote coordination and knowledge sharing**: Create national guidance resources, foster stakeholder collaboration, and profile the benefits of RW through a coordinating body like the Riverwoods Initiative.

**Diversify funding for river woodlands**: Develop sustainable finance models, including carbon markets and green financing, while tailoring evidence to private sector needs to unlock resources for large-scale restoration through long-term investments.

**Shape policy for river woodlands**: Provide targets for river woodlands that are aligned with national policies, integrate cross-sector objectives, and promote adaptive management strategies that address both local and regional priorities. Powerful ‘hooks’ lay within the prioritised topics of biodiversity, flooding and drought planning, soil health and climate resilience policy-themes. Overarching policies such as SNAP3, SBS, Soils Framework, National Planning Framework 4 and Water Framework Directive should set the overall need for holistic multi-benefit (cross-policy), landscape scale outcomes. In turn, these should guide specific implementation steps in detailed strategies like the Woodland Carbon Code, Scotland’s Rural Development Program, River Basin Management Planning and Green Health Initiatives.

# 1 Introduction

River woodlands (RW) are vital for healthy and biodiverse rivers and surrounding ecosystems (Forest Research, 2024). They can be defined as trees, woodlands and forests, either natural or planted, around the bank and alongside a natural body of freshwater (especially a stream or river but also including lochs) (Dufour, S. & Rodríguez-González, P.M., 2019). River woodlands include trees within the riparian zone, floodplain, and gorges (see glossary for definitions). Potential benefits of RW include reducing and mitigating effects of water pollution and erosion, intercepting air pollutants, water stress mitigation and adaptation, flood risk alleviation, increases in carbon storage, soil health, biodiversity, food and biomass production and utilisation, and health, wellbeing, heritage and community involvement (Ogilvy *et al.*, 2022). They can thereby help mitigate the effects of the biodiversity and climate crises.

Morphological surveys during 2015-16 revealed generally poor condition of bankside vegetation, including woodland, in ~55% of the linear bank lengths of Scotland's river ecosystems (>10 $km^2$ catchments in Water Framework Directive reporting) (Ogilvy *et al.,* 2022). For such reaches, the lack of diversity of trees, shrubs, species rich grasslands, or wetlands can have significant consequences for ecosystem functioning and services. River woodland restoration has therefore gained significant interest from a diverse array of stakeholders across Scotland. For example, many third sector projects and groups are supporting RW creation and management, with objectives of restoring natural habitats, reducing pollution, and enhancing the resilience of river ecosystems. Catchment partnerships and fishery trusts are leading the way in terms of getting trees on the ground. The Tweed Forum has been delivering native RW creation throughout the Tweed catchment for over two decades, planting 1.5 million trees across more than 1,100 hectares, with the Dee, Spey and South Esk catchments approaching similar targets. Umbrella projects in support of woodland creation include the Riverwoods Initiative, led by the Scottish Wildlife Trust (SWT), and the Northwoods Rewilding Network, a Scotland-wide chain of landholdings convened and coordinated by SCOTLAND: The Big Picture.

The creation and restoration of RW also has multiple links with current policy initiatives, notably the Scottish Biodiversity Strategy (SBS), Scotland's Forestry Strategy (SFS), Scotland's National Flood Resilience Strategy (SNFRS), and Third Land Use Strategy (STLUS), the Natural Environment Bill (NEB), and the Scottish National Adaptation Plan (SNAP3). For example, the SBS states that by 2045 "Riparian woodland will have expanded as a key component of restored rivers, reducing the average temperature of our rivers and burns, leading to increases in freshwater fish species and other wildlife". In parallel, SNAP3, also set out the importance of healthy, resilient, biodiverse ecosystems in helping to adapt to the changing climate. Scottish Forestry's riparian target area identified around 175,000 hectares of riparian land that has the potential for woodland planting to deliver multiple benefits. For these targeted areas, the Scottish Government's Forestry Grant Scheme (FGS) offers enhanced payment rates where multiple benefits can be achieved. This includes riparian planting as a nature-based solution for flood risk management, which aligns with the SNFRS. Furthermore, they also support RW creation as a priority within river restoration projects. Both national parks (Cairngorms and Loch Lomond) have forest strategies, including RW targets.

Despite the existing support and activity around RW, further action is needed to enable the establishment of healthy river woodlands across Scotland, at a scale sufficient to ensure their resilience and deliver lasting benefits to society. Lack of information and understanding of RW may impede the ability to motivate, justify and design interventions in support of RW.

In 2022, Ogilvy *et al.,* published the Riverwoods Evidence Review (hereafter referred to as the 2022 review), where they used metrics on the quality of science to establish evidence status for RW benefits and identified areas of weaknesses in the evidence base, both with respect to the ecosystem functions associated with RW and the effects of restoration and creation measures. These evidence gaps span various disciplines, including biology, hydrology, ecology, and human health and cover all main benefit areas as outlined above. The 2022 review revealed a moderate to strong level of evidence for a positive effect for most functions indicated (Table 1). However, for many benefit areas there were questions around place and scale (both in space and time), and thereby transferability of potential benefits across diverse and changing environments in Scotland (Ogilvy *et al.,* 2022).

The 2022 review was also unable to determine what evidence gaps were most relevant for enabling different stakeholder groups to support RW. Because healthy RW can provide many ecosystem goods and services, many different societal groups could benefit from or depend on them; so, in principle this should lead to widespread support and involvement in managing and restoring RW. However, in practice – as for many nature-based solutions (European Investment Bank, 2023) – pro-environmental groups in the third sector, and environmental agencies in the public sector, tend to be most active in supporting RW. It is important to understand if providing more or strengthening existing information, or better disseminating information on certain topics may help to motivate and unlock more support from other groups.

## Aim and objectives

The overarching aim of this work was to engage with the literature and a wide range of stakeholders to update and prioritise the research and development (R&D) needs identified in the 2022 evidence review. Although not a formal policy-review, we link the stakeholder priorities and evidence requirements with topics in key policies and strategies aligned to RW outcomes.

Specifically, the objectives were to:

1. Provide an updated scientific literature assessment of the evidence for RW benefits, focussing on the specific gaps considered in the 2022 review as important to knowledge and implementation in Scotland and also newly proposed knowledge gaps from stakeholders;
2. Engage with a wide range of stakeholders from academia, and public, private and third sectors (including policy, nature finance and business representation) across Scotland to identify additional evidence gaps across benefit areas and prioritise evidence needs promoting improved establishment and management of healthy and resilient RW systems;
3. Identify opportunities and mechanisms to address these gaps to enable investment in new and extended RW, and improved/restored river environments.

The project informs future work and priority research areas to facilitate the creation of healthy and resilient river systems through enhanced riparian and floodplain management in Scotland. Additionally, we provide recommendations and identify opportunities to address these gaps, thereby enabling new and extended RW and the improvement or restoration of riverscape environments.

**Table 1. Simplified evidence summary across RW benefits areas taken from the 2022 review (Ogilvy et al., 2022) and forming the starting context for the present study. The strength of evidence presented is based on quality of studies recognising empirical data quantifying positive effects (see footnote).**

| River woodlands benefits | Strength of evidence for functions of river woodlands | | | |
|---|---|---|---|---|
| | **Very strong** | **Strong** | **Moderate** | **Weak** |
| **Clean water** | Stabilising riverbanks by tree rooting | Controlling nitrogen pollution<br>Controlling phosphorus pollution<br>Controlling excessive algae & periphyton<br>Capturing sediment pollution<br>Aerial pesticide interception | | Capturing pathogens |
| **Conserve Biodiversity & Ecosystems** | Supporting aquatic processes | Supporting other species<br>Supporting river hydro-morphological processes and diversity | Providing habitat connectivity & supporting genetic diversity | |
| **Climate action: water stress & drought adaptation** | | Modifying local climate conditions: shading and cooling air | Modifying local climate conditions: hydraulic lifting | Maintaining water yields & low flows |
| **Climate action: Flood risk alleviation** | | | Slowing the flow<br>Reducing coarse sediment delivery and siltation of channels | |
| **Climate action: Carbon** | | | Carbon sequestration & carbon storage | |
| **Clean air** | | Intercepting air pollutants | | |
| **Sustaining soils** | | Reducing soil loss | | Improving soil health |
| **Good human health** | | Exposure to woodland<br>Cooling air | | |
| **Wild fish and angling** | | Regulating local climate through shading | Providing food for fish | Improving habitat for fish with large woody material |
| **Sustain food production** | | Supporting pollination<br>Providing shelter & shade for livestock | Providing fodder for livestock | |
| **Clean energy Biomass** | | Provision of biomass for energy | | |

Note: In the 2022 review strength of evidence was determined as quality and number of studies, weighted towards those with positive effects (defined in Ogilvy *et al*., 2022). It is important to return to the evaluations in each of the chapters of the 2022 review to understand the specific functions, type of woodlands and scale of application that these classifications refer to. Benefit groups use terminology of Common International Classification for Ecosystem Services (CICES v5.1), common also to the UN Sustainable Development Goals and widespread business and government usage and adopted for general usage in the present study.

# 2 Methods overview

The project adopted a multi-phase approach combining stakeholder engagement activities and an evidence review process to update and prioritise research and development (R&D) needs for RW restoration in Scotland. The stakeholder engagement gathers opinions and perceptions on the evidence needs while the update to the evidence review identifies formal areas of evidence gaps (Figure 1).

Detailed versions of the various project phases are available in appendices and data are available in the project database Appendix 6.

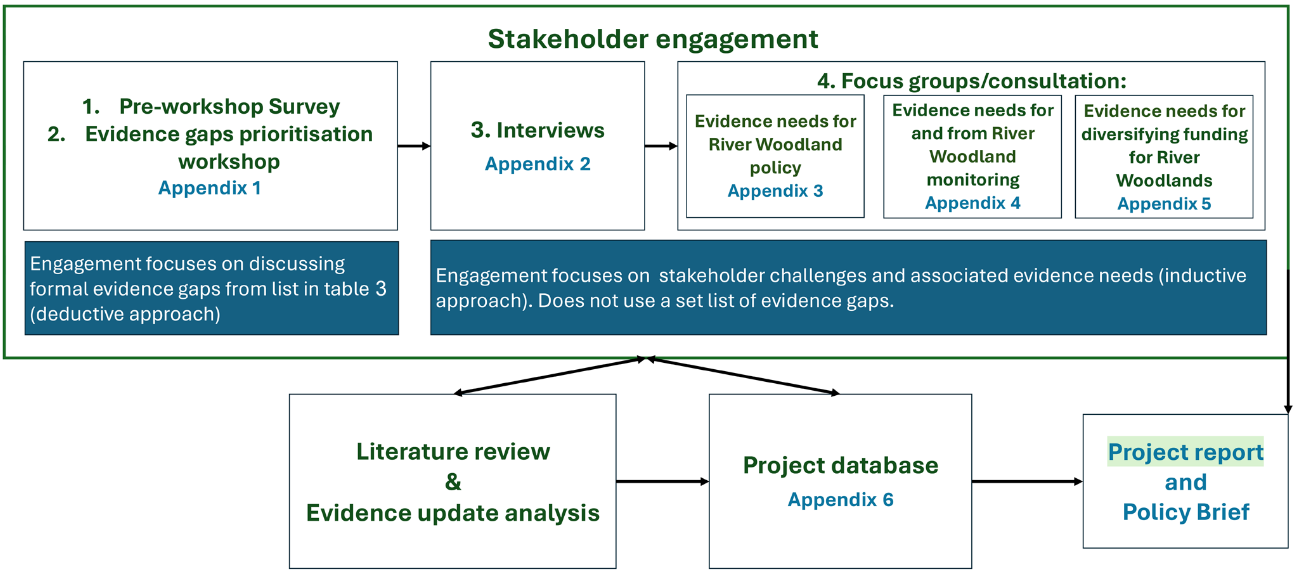


**Figure 1. Overview of the Project structure and activities comprising of the stakeholder engagement phases, evidence review analysis, reporting and delivery with associated deliverables.**

## 2.1 Evidence review

The 2022 review used mixed methods to derive statements and rankings of the strength of evidence, specific to riparian woodland types covered. A second step gave detailed statements on important remaining knowledge gaps. These strength of evidence and gap statements were the starting point for the current review of 51 identified R&D gaps related to RW benefits (Figure 2). We derived search terms for the present study from the detailed gap statements in the 2022 review (presented in tables, sections 3.3 to 3.10) and nine gaps from direct stakeholder engagement. The large number of gaps necessitated rapid evidence review methods (Varker *et al.,* 2015), using Google Scholar as the literature search engine for its wider coverage of literature and superior ability to identify grey, or unique, literature (Martin-Martin *et al.,* 2018).

The key comparisons and interrelationships between the past and current reviews are:

i. A key rationale for the update is the focus on the specifics of areas concluded as knowledge gaps relevant to RW implementation in the UK regardless of the overall evidence strength identified previously (Table 1), i.e. even overall strong evidence classified topics by the 2022 method had specific associated knowledge gaps of process-understanding and practice impact that may be the most important to stakeholders.

ii. A new consistent examination of global literature over the last decade (2014-2024), considering metadata on study robustness (scale, duration, controls) and climate zone would allow transferable knowledge of UK-relevance to be assessed against these gap specifics.

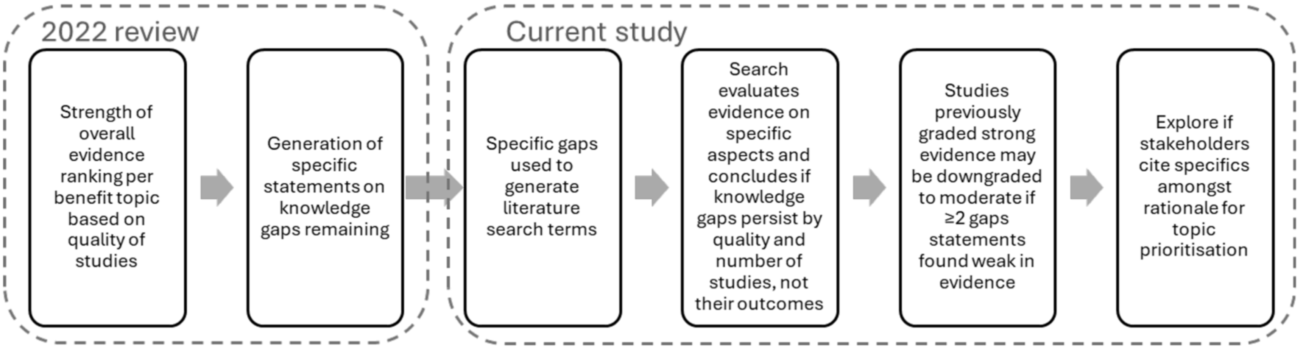


**Figure 2. Summary of the steps of the previous 2022 review, leading to the current specific gap review. For details see Appendix 6.**

iii. The 2022 review method incorporated quality of study into strength of evidence classifications, emphasising where empirical data showing positive effects on functional outcomes was provided. The summary of the 2022 review, used as the starting point for the current project (Table 1), simplifies aspects of specificity of these data to studies scales (especially water quality effects of plot vs whole catchment outcomes) and river woodland types covered. Our understanding of the details of these was used in later stakeholder consultations (after the survey stage) and in the reviewing against the specific gap statements. We conclude here following an updated reviewing process if the specific gaps remain and compare this to stakeholder needs.

iv. Any reclassification of overall evidence level from the 2022 review is made on the basis of the impact of two or more specific knowledge gaps not satisfied by findings relevant to UK conditions, such that 'strong' evidence is not used (downgraded to moderate).

v. Despite methodological differences between the 2022 and present review, reducing strongly ranked topics to moderate where specific gaps persist supports our recommendations for future resourcing towards addressing that gap, mostly where the gap aspects have proven importance, considering the stakeholder analysis here.

The results of our review are in a database format (Appendix 6) where the gap specifics, search terms and results, selected top five publications, metadata on study quality, context, climate zone relevance and findings are given (alongside a 'user-guide'). Searches, limited to the last decade (2014-2024), focused on literature not already covered in the 2022 review. Relevant papers, screened by title and key words, were saved to Google Scholar libraries and judged by abstract for relevance in addressing the gap. Those included in the 2022 review were discounted at this stage. A longer list of up to ~30 papers were read in whole or part (considering the full wording of the stated gap detail) to arrive at a final maximum five final papers per gap, selected for interpretation of findings and metadata extraction into the database. Metadata focus differed according to study type between: primary studies (scale, duration, controls), modelling (data robustness) and review type studies (countries covered, number of studies). Climate zones were summarised by conversion of study site (for primary studies) latitude and longitude coordinates into global climate zones (https://koeppen-geiger.vu-wien.ac.at/present.htm). River woodland types (see Figure 2; full origins in Appendix 6) were used to categorise what types of woodland the studies covered: types a to f concerned semi-natural and natural RW, floodplain and gorge woodland; types g to l covered management buffer zones using woodland; types j to l covered large woody material.

Importantly, where studies allowed, a final strength of evidence statement was developed covering the specific gaps brought forwards from the 2022 review. The updated review results (sections 3.3-3.10) and the results database (Appendix 6) concludes each reviewed gap with a statement of whether the knowledge gap remain inadequately addressed or alternatively is covered by robust studies of relevance to UK geoclimatic conditions.

## 2.2 Stakeholder Engagement

Our stakeholder engagement sought to refine detailed priorities within and between the R&D gaps, identify additional gaps or nuances, and identify areas where stakeholders needed further evidence even though some evidence already exists (Project Objective 1). All of the phases of engagement were motivated by understanding where new evidence would prove the most useful to enable practice (Project Objective 3).

We were mindful that evidence gaps may not be the only challenge to supporting RW, and so this contextualised our engagements and prioritisation; and allowed participants to acknowledge if evidence gaps were not a problem in their view, or if only certain knowledge topics should be prioritised, especially given the constraints of limited funding and time in a changing environment.

In the first two phases of engagement (survey and workshop), we used a list of 'evidence gap statements' that had been derived from refining the 51 evidence gaps identified in the 2022 review (Table 3). These were used as a starting point guide for discussion, refinement, addition and prioritisation exercises. This approach, focused on formal evidence gaps across diverse disciplines, tended to attract stakeholders with expertise and familiarity with the existing literature, as well as those with strong opinions on potential directions for future research. However, collaborative research prioritisation processes often face challenges in extending participation to a broader range of stakeholders (Dey *et al.*, 2020). To foster greater inclusivity, our second and third phases of engagement involved interviews and focus groups, focusing on open questions on evidence needs rather than the initial list of evidence gaps. A breakdown of the stakeholders engaged throughout the various phases of the project is available in Table 2.

The process of stakeholder engagement received prior approval from the James Hutton Institute research ethics committee. All personal data collected by the project were processed and managed confidentially and securely in accordance with UK and EU GDPR.

### 2.2.1 Survey and workshop

The survey and workshop aimed to identify barriers to RW restoration, prioritise the evidence gaps identified in the 2022 review, and uncover additional gaps. Conducted between April and July 2024, the survey was hosted on SnapSurveys by Aberdeen University and included 37 rephrased gap statements derived from the 2022 Riverwoods Evidence Review. The target audience included individuals and organisations with an interest or experience in RW restoration.

The survey was disseminated to an initial list of stakeholders (known to the research team and project steering group) who were also asked to share it; and it was also disseminated via email campaigns, social media, and professional networks. It featured a mix of closed-ended questions, Likert-scale items, and open-ended fields for additional comments. This phase allowed the participants to attribute levels of importance to each gap (meaning how important it was to address this evidence gap) which provided a first level of prioritisation.

**Table 2. Invited and participated stakeholders by sector, with participation detailed for each event.**

| | Academia (Including, Research institutes, University researchers across all expertise e.g. biodiversity, hydrology, public health) | Private sector (Including Consultancies, Private businesses, Private energy companies) | Public sector (Including Environmental agencies, Government, Health agencies, public water supply) | Third sector (Including eNGOs and conservation organisations) | Total |
|---|---|---|---|---|---|
| **Directly invited individuals** | 50 | 57 | 97 | 91 | **295** |
| **Total individuals engaged*** | 24 | 23 | 36 | 32 | **115** |
| **Survey** | 19 | 9 | 20 | 18 | **66** |
| **Workshop** | 3 | 3 | 8 | 1 | **15** |
| **Interviews** | 2 | 6 | 3 | 2 | **13** |
| **Policy focus group** | 0 | 2 | 13 | 8 | **23** |
| **Monitoring focus group** | 3 | 2 | 1 | 3 | **9** |
| **Diversifying funding** | 0 | 3 | 4 | 1 | **8** |
| **Other (e.g. email, meetings)** | 0 | 3 | 1 | 2 | **6** |

*Note that some individuals participated more than once, so that the total individuals engaged is smaller than the sum of participants in each of the events.

**Table 3. Rephrased gap statements derived from the 2022 review, taken into the first stages (survey, workshop) of stakeholder consultations. Additional gap statements marked as 'New' are also included and were put forward by the stakeholders. The leftmost column shows the eight themes for these benefits considered in sections 3.3 to 3.10 of this report.**

| | Specific benefits | Focus areas for stakeholder consultation (gap statements used in survey and workshop) |
|---|---|---|
| **Water pollution reduction and air pollution interception** | Clean water: general | [1] The understanding of the ecological and chemical status of headwaters nationally to support RW planning. |
| | | [6] The effect of establishing RW on pollution swapping aspects. |
| | Clean water: Stabilising riverbanks | [2] The way RW types and placement (scale, positions across differing soils and slopes) contribute to stabilising river banks and mitigating other sediment sources to streams. |
| | Clean water: nitrogen and phosphorus pollution | [3] The effect of RW types and designs on catchment nutrient pollution, including as part of wider catchment diffuse pollution measures. |
| | Clean water: excessive algae and periphyton | [4] The role of RW shading in mitigating excess algal growth in streams (especially to counter climate change effects). |
| | Clean water: controlling pesticides | [5] The effect of RW characteristics (e.g. creation, age and composition) on mitigating pesticide pollution for waters. |
| | Clean water: Capturing sediment pollution | [7] The effect of RW on the transport of coarse sediment to and within waterways. |
| | Clean water: capturing pathogens | [8] The influence of river corridor tree rooting on water infiltration and physical particle trapping to mitigate pathogens (microbial contaminations). |
| | Clean air: mitigating air pollution | [17] The effect of different RW designs on pollution swapping resulting in air pollution (e.g. dissolved nitrate to airborne nitrogen oxides). |
| **Drought/water stress** | Modifying local climate: shading, cooling, hydraulic lifting; water supplies | [9] River woodlands' contribution to maintaining river flows, especially during dry periods.<br>[10] The effect of different RW tree species on moisture content in different soils. |
| | Tree species adaption to drought | [11] Understanding which RW tree species can best adapt to drought periods in Scotland. |
| **Flood risk alleviation** | Slowing the flow | [12] The effect of RW type, age, placement and scale on mitigating downstream flood risk. |
| | | [14] The effect of leaky barriers and large woody materials (including design and construction aspects) in mitigating flood peaks at the catchment scale. |
| | Reducing coarse sediment delivery and siltation | [13] The effect of human made leaky barriers and large woody materials on watercourse sediment loads. Leaky barriers are part of the measures and techniques used for flood management. |
| **Carbon storage** | Carbon sequestration and storage | [15] The comparison between carbon storage in wooded versus non-wooded zones along different Scottish rivers. |
| | | [16] The effect of RW restoration and creation on greenhouse gas emissions. |
| **Sustaining soils** | Improving soil health | [18] The effect of RW on soil health, structure, biodiversity, fungi, microbes, soil carbon storage, nutrient cycling. |
| | Soil loss impacts | [19] The physical and economic effects of soil loss in wooded versus non-wooded river corridors. |
| **River corridor biodiversity and habitat** | Aquatic processes | [20] The effect of the expansion of RW on biodiversity. |
| | Supporting species | [22] The characterisation of native RW' tree structures and species composition across Scottish regions to inform restoration practices benefitting ecological condition. |
| | | [23] The interactions of large herbivores (such as deer or beavers) with RW restoration and creation |
| | | [24] The characterisation of habitat benefits of RW for specific key species e.g. birds, bats, freshwater pearl mussels, aquatic invertebrates and lichens. |
| | Habitat connectivity and genetic diversity | [21] The understanding of the genetic diversity of RW native tree species in Scotland, and the implications for sourcing trees and tree nurseries. |

| Table 3 continued. Rephrased gap statements derived from the 2022 review, taken into the first stages (survey, workshop) of stakeholder consultations. Additional gap statements marked as 'New' are also included and were put forward by the stakeholders. The leftmost column shows the eight themes for these benefits considered in sections 3.3 to 3.10 of this report. | | |
|---|---|---|
| | **Specific benefits** | **Focus areas for stakeholder consultation (gap statements used in survey and workshop)** |
| **River corridor biodiversity and habitat** | Morphological outcomes | [25] The understanding of the type of vegetation and space required for achieving specific river morphological outcomes. |
| | Regulating climate by shading | [32] The cooling, warming and insulating effect for fish under different RW canopies, with or without the influence of groundwaters. |
| | Providing food for fish | [31] The effects of RW on the availability of invertebrate food sources for salmonids. |
| | Biodiversity and ecosystems | [26] The effect of the presence of different species (trees, wider vegetation, terrestrial and aquatic animals) on catchment-scale nutrient recycling through ecosystems and trophic levels. |
| | New: Biodiversity and ecosystems | [44] The interactions between invasive non-native species and RW |
| | | [45] The effects of habitat fragmentation on RW. |
| | | [46] The effect of plant pathogens on the expansion of RW. |
| | | [47] The understanding of how ecological functions of RW interact spatially with human factors. |
| **Health, wellbeing,** | Exposure to RW; cooling air | [27] The mental and physical health outcomes of RW. |
| | | [28] How RW can be integrated to urban settings to optimise cooling for human health benefits. |
| | | [29] The economic effects of RW on the NHS as an organisation. |
| | | [30] The role of RW in changing DOC concentrations and forms that impact drinking water treatment (harmful disinfection by-products). |
| | Social, cultural and heritage (stakeholder additional topics) | [40] The relationship (synergies and impacts) of restoration projects on local cultural heritage and archaeological sites. |
| | | [41] The understanding of community preferences, social and political perceptions of RW restoration. |
| | | [42] How mechanisms for developing restoration projects are socially acceptable, just and beneficial to local communities. |
| **Food and biomass** | Shade for livestock; Shelter for livestock; Providing fodder for livestock | [33] The relationship between RW and livestock management in different landscape settings (e.g. different soils, upland vs lowland). |
| | | [34] The nutritional and medicinal effects of tree fodder for livestock productivity. |
| | Supporting pollination | [35] The understanding of how to design heterogeneous landscapes (to include RW) in order to optimise crop pollination. |
| | Provision of biomass for energy | [36] The effect of short rotation coppice (fast growing trees planted for fuel e.g. willow, poplar) RW on water and soil quality. |
| | | [37] The viability of local to regional biomass markets for RW products, including economic benefits to small producers such as farms, specific to Scotland. |
| **Additional topics added after the survey** | New: Monitoring | [38] The integration of technical challenges (e.g. designs for outcomes) with applied challenges involved in RW expansion (e.g. grazing reduction, restoration vs natural regeneration). |
| | | [39] Strategies for developing robust monitoring of outcomes considering scales. |
| | New: Finance | [43] Developing evidence-based financial incentives and mechanisms. |

Building on the survey findings, a one-day stakeholder workshop was held in June 2024, with 15 participants chosen from the project stakeholder list and via snowball sampling (suggestions by other participants). The workshop aimed to refine and prioritise the updated list of 47 evidence gaps (10 were added after the survey). A carousel exercise formed the core activity, where participants, divided into four mixed groups, rotated through tables, to discuss, vote on and rank evidence gap cards. This aimed to provide a second level of prioritisation (this time relative). Facilitators documented key points of consensus and disagreement. Participants were selected to represent diverse sectors relevant to RW restoration.

Data analysis for the survey and workshop involved both quantitative methods and qualitative thematic analysis. This phase provided a foundational understanding of broad areas of stakeholder priorities and perceptions, key focus topics for in-depth engagement as well as further stakeholders to engage with. A detailed version of the survey and workshop approaches and results is available in Appendix 1.

### 2.2.2 Interviews

Semi-structured interviews were conducted with 13 stakeholders from September to November 2024. The questions and participants were deliberately oriented around including organisations not already well represented in the prior phase of engagement. Participants came from several sectors: farming and land use, private sector/businesses, planning, and health, as well as restoration practitioners. This phase allowed the Project team to involve stakeholders who did not get the opportunity to engage in the first two phases as well as stakeholders who did not feel comfortable engaging with formal evidence gaps. The interviews explored broader challenges in RW restoration, with questions addressing current barriers and required evidence, and challenges specific to each stakeholder group. Sessions were conducted via Microsoft Teams, lasting 30 to 60 minutes. Recordings were transcribed and analysed using thematic coding, focusing on barriers and evidence needs. Specific evidence needs raised during the interviews and linking to the initial list of gaps, were used to refine the initial prioritisation (survey and workshop). A detailed version of the interviews approach and results is available in Appendix 2.

### 2.2.3 Focused Topic Engagement

Following the above engagements, three priority topics emerged: policy challenges, monitoring, and diversifying funding. These topics were explored through tailored engagement strategies that took place between October and December 2024. Each of those activities are detailed in Appendices 3, 4 and 5 and considered in the results of this report.

#### Policy focus group

The policy focus group, held at the end of November 2024 built on insights from previous phases to address evidence needs related to policy challenges. A pilot session in September 2024 tested the discussion framework, refining questions to focus on challenges, evidence needs, and actionable pathways. The online focus group engaged 18 participants through breakout room discussions facilitated by moderators. Pre-identified challenges and evidence needs were summarised in a shared online document, which participants used to contribute asynchronously. This iterative process incorporated insights from both live discussions and online contributions, maximising inclusivity and comprehensiveness. A detailed report on this activity is available in Appendix 3.

#### Monitoring focus group

Conducted between October and December 2024, the monitoring focus group included experts such as academics, practitioners, consultants, and regulators. Discussions focused on three themes: evidence gaps, methodological improvements, and policy implications. Five guiding questions were used to structure discussions, covering topics such as citizen science, data synthesis, and funding opportunities linked to monitoring. Outputs from the focus group informed recommendations for enhancing monitoring practices and linking them to policy and funding mechanisms. A detailed report on this activity is available in Appendix 4.

#### Diversifying funding consultation

Feedback on the challenges of diversifying funding reflected the challenge of recruiting ‘new’ private sector organisations to discuss RW. We organised a consultation process which was disseminated widely in relevant stakeholder networks to seek feedback - even brief – from participants from or with knowledge of private sector actors who might invest in RW. An initial briefing was circulated to relevant groups, including the Riverwoods Finance

Group and Scottish Nature Finance Pioneers. Stakeholders were invited to provide feedback via Basecamp (a project management and team collaboration tool), email, an MS Form or direct conversations/interviews. Questions focused on identifying evidence needs for diversifying funding, recommendations for addressing these gaps, and feedback on the briefing itself. Responses were analysed and integrated into a revised consultation report, ensuring a broad representation of perspectives from stakeholders less traditionally involved in RW restoration. A detailed report on this activity is available in Appendix 5. The information collected in all of this phase of topic engagements was used to supplement and enhance the qualitative analysis previously carried out on the results of the phase 1 of engagement

#### 2.2.4 Presentation of the evidence review stakeholder engagement and prioritisation

All the stakeholder inputs gathered across the project were synthesised, linking evidence needs and perceived gaps to the formal update of the evidence review. Stakeholder engagement data – including survey responses, workshops, interviews, focus groups, and consultations – were analysed to identify emerging patterns and sector-specific concerns. Details of individual engagement activities are provided in Appendices 1–5, with supplementary data in Appendix 6.

Section 3 presents an overview of the evidence review and stakeholder findings, followed by 9 thematic sections on RW benefits. Each thematic section follows a structured format: introduction, review results against identified gaps (for details see Appendix 6), stakeholder perspective including connections to relevant policies (Appendices 1–5), and a synthesis linking stakeholders' stated evidence needs to the formal existing evidence. We should note that this does not represent an exhaustive review of the policies on each topic. We explored a range of relevant policies to point to relevant areas of evidence needs using Notebook LM and word search. These results informed a summary prioritisation matrix (X: Strength of evidence; Y: Stakeholders priorities) presented in section 4, Figure 5.

Section 4 discusses the prioritisation of evidence needs of the various benefit areas, across all stakeholders and in the context of overall challenges for RW. It also identifies pathways and recommendations to address priority evidence needs. The overall prioritisation of evidence gaps was (step 1) based on the initial ranking from the survey and workshop, and (step 2) adjusted to reflect additional (qualitative) insights from interviews and focused engagement. For step 1, stakeholders initially ranked gaps which were then organised into three priority clusters (low, medium, and high). Where further engagement highlighted new priorities, through qualitative analysis during step 2, gaps were moved to a higher priority category; none were downgraded from their initial ranking  the survey and workshop.

# 3 Synthesis of evidence review and stakeholder engagement across benefits areas

## 3.1 Overview of evidence review results, confirmation and re-evaluation of specific gaps

Sections 3.3 to 3.11 address evidence within thematic areas. Here the overall results are summarised. In total, 116 publications were read and summarised across the 60 R&D gaps reviewed, comprising 60 primary data studies, 29 modelling studies, 29 review or synthesis papers and 9 reports (Figure 3a). Amongst primary studies, planted riparian buffers were the most frequently reported RW type followed by semi-natural RW (15.3%) and restored or planted RW (13.5%) (Figure 3b). Thirty-seven studies (57%) conducted within a temperate, fully humid warm climate zone (Figure 3c) have maximum relevance to Scottish conditions, others are discussed relative to study constraints.

Using the newly assessed literature (additional to that covered in the 2022 review) to assess the specific gaps statements, we found a varied coverage of papers and additional knowledge (Tables 4 to 11). In some cases zero to fewer than five publications were found covering the topic (it was then more likely that studies in non-temperate climate zones feature in our review results).

Following the methodology (Figure 2), we confirmed the majority of specified gaps to remain, but also eight cases where previously strong classification in the 2022 review was downgraded to moderate due to persistence of multiple specific gap areas. Table 4 (and schematic key; Figure 4) summarises the overall evidence strength for different topics, combining the updated specific gaps review with the 2022 review. Specific topics (in blue) are ordered from right to left according to strong to weak evidence. The use of an arrow shows the eight cases where topics previously classified as strong (or very strong) were downgraded to moderate on the basis of having more than one associated specific gap without adequate knowledge. Most (n=18) topics were confirmed as having a similar level of evidence as in the 2022 review (black bold font). We also reviewed new topic areas raised by stakeholders in the survey consultation of the current study and placed these at evidence levels for the first time (Table 4). The perceived gap on monitoring strategies had a large body of international evidence, whilst new finance and biodiversity topics had some aligned studies; but all were considered as moderate evidence. The community and heritage aspects had no research and were considered weak evidence.

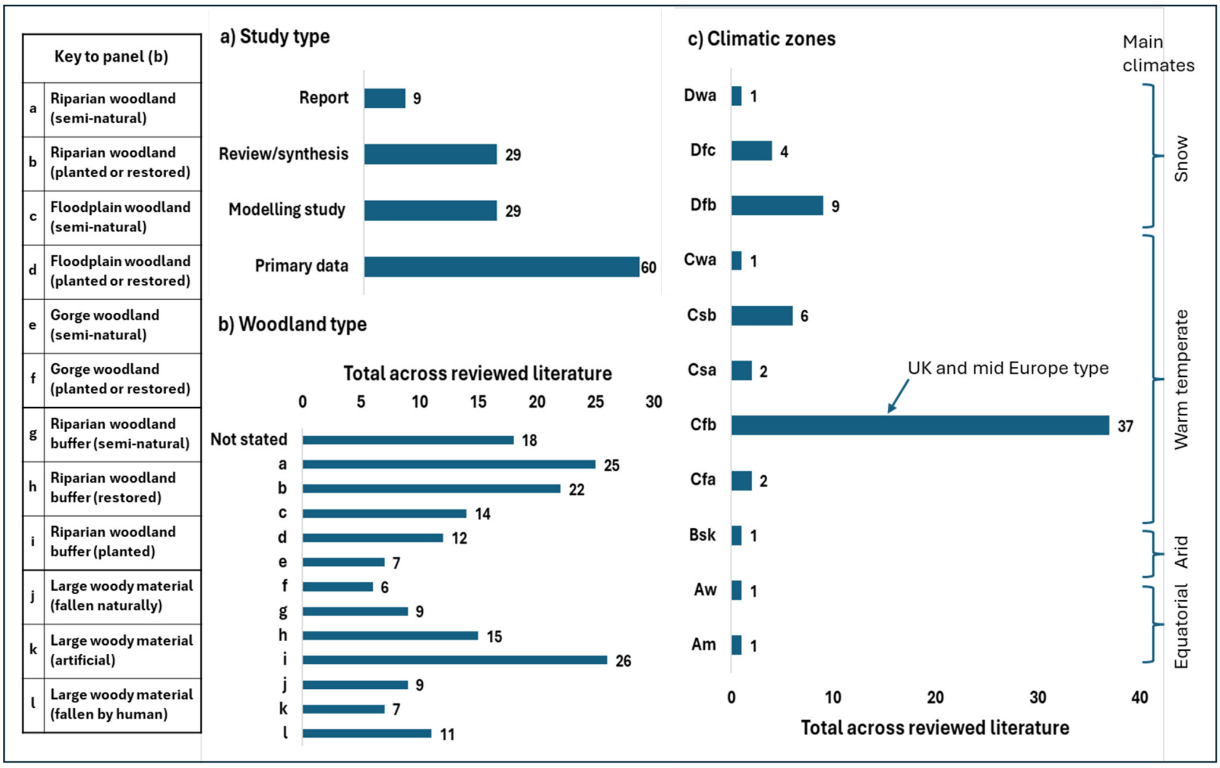


**Figure 3. Summary of metadata from the review of literature by (a) paper type, (b) woodland types considered (summarised in table, often multiple types per study) and (c) climate zones according to the Köppen-Geiger classification (see: https://koppen.earth/).**

To illustrate, take the example of understanding the benefits of controlling N pollution, in the benefit theme of *Clean water*. The 2022 review suggested strong evidence but specific knowledge gaps for: empirical evidence of reduction of catchment nutrient exports from RW; understanding of woodland design and management for pollution swapping; and evidence of scaling effects towards catchment scales. We found the specifics of these gaps only weakly covered by two review papers. We conclude that weak areas of specifics should be considered against the earlier strong classifications. Here we downgrade the evidence level to moderate on the basis of persisting knowledge gaps of importance to UK implementation because a 'strong' rating does not conclude a need for research to address gaps. If riparian woodland is to be positively incentivised through credit or green financing based on nutrient outcomes this report should correctly drive further research for N outcomes at catchment scales against woodland designs, application scale and with regard to pollution swapping.

Table 4 also shows key supporting metadata from the current review in terms of the number of searches, number of studies, study type and climate zones. Up to five of the most relevant studies were selected, where available (red or blue cells in the metadata column, blank cells (or 'no studies') indicating lack of available literature). This reflects aspects of our considerations of whether specifics were well to poorly addressed in the current review update. These results inform section 4.4 synthesis of strength of evidence against priorities and pathways to address these. The red numbering (rightmost column, Table 4) shows the high prioritisation of gaps.

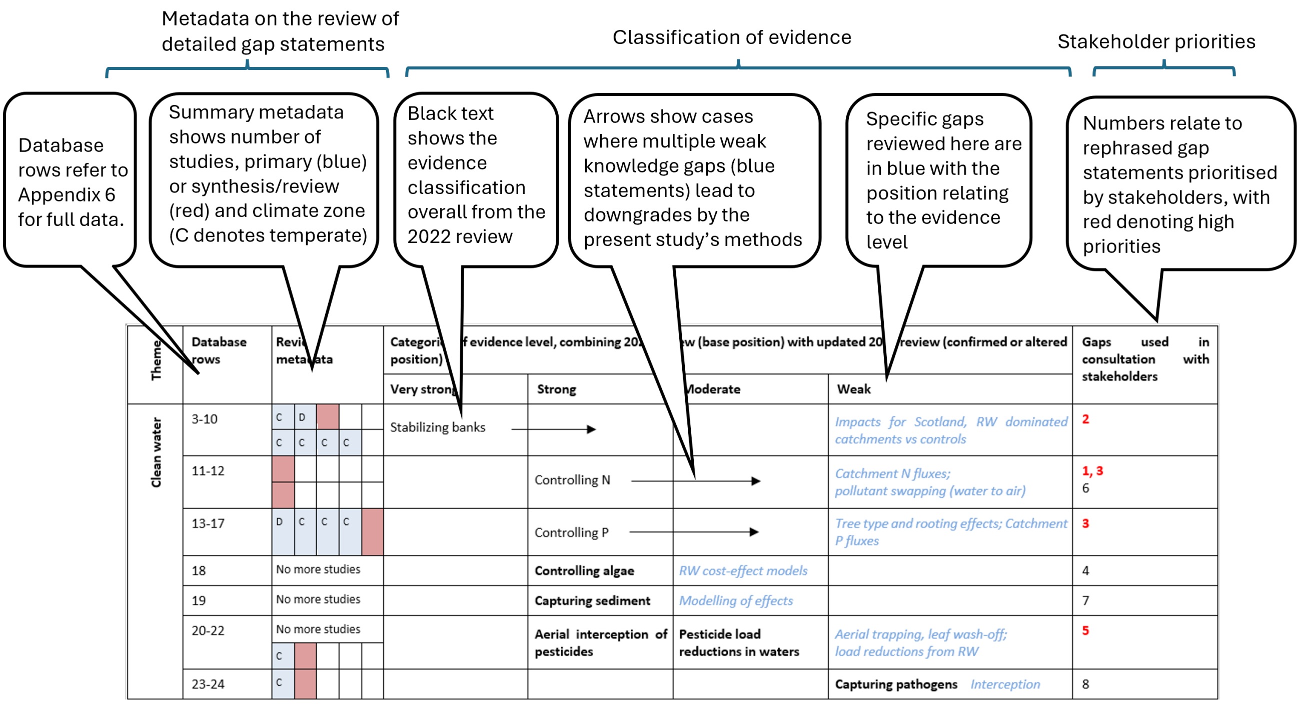


**Figure 4. Schematic key to Table 4.**

**Table 4. Mapping of evidence levels (black text, with horizontal arrows; combining 2025 review of specifics with previous 2022 review strength of evidence ratings), gaps area topics (blue and italic text), summary review metadata (left columns) and stakeholder gap priorities (red underlined numbering, right column). See Figure 4 for the key.**

| Theme | Database rows | Review metadata[1] | Very strong | Strong | Moderate | Weak | Gaps used in consultation with stakeholders |
|---|---|---|---|---|---|---|---|
| | | | *Categories of evidence level, combining 2022 review (base position) with updated 2025 review (confirmed or altered position)* | | | | |
| **Clean water** | 3-10 | C D<br>C C C C | Stabilizing banks by tree rooting → | → | | *Impacts for Scotland, RW dominated catchments vs controls* | 2 |
| | 11-12 | | | Controlling N → | → | *Catchment N fluxes; pollutant swapping (water to air)* | 1, 3<br>6 |
| | 13-17 | D C C C | | Controlling P → | → | *Tree type and rooting effects; Catchment P fluxes* | 3 |
| | 18 | No more studies | | **Controlling algae** | *RW cost-effect models* | | 4 |
| | 19 | No more studies | | **Capturing sediment** | *Modelling of effects; Floodplain woodland effects* | | 7 |
| | 20-22 | No more studies<br>C | | **Aerial interception of pesticides** | **Pesticide load reductions in waters[2]** | *Aerial trapping, leaf wash-off; load reductions from RW* | 5 |
| | 23-24 | C | | | | **Capturing pathogens** *Interception* | 8 |
| **Conserve Ecosystems** | 25 | No more studies | **Supporting aquatic processes** | | | | 20, 25, 22, 26 |
| | 26-29 | D C C | | **Supporting other species** | *Large herbivore interactions in RW establishment* | | 23, 24 |
| | 30-35 | D C C<br>Unclear gap | | | **Habitat connectivity & genetic diversity** | | 21 |
| **Drought** | 36-38 | D<br>C | | **Modifying local climate conditions: shading & cooling air** | **Modifying climate: hydraulic lifting** | *Applied modelling of relieving water stress; Study effects on soil moisture* | 10 |
| | 39-46 | C B C<br>C C<br>No more studies<br>C | | | | **Maintaining water yields & low flows**<br>*Tree, soil, climate interactions; National RW targeting tools; floodplain RW water storage; protection of water supplies.* | 9 |
| | 47 | No more studies | | | | **Tree species adaptation to drought[3]** | 11 |

**Table 4 continued. Mapping of evidence levels (black text, with horizontal arrows; combining 2025 review of specifics with previous 2022 review strength of evidence ratings), gaps area topics (blue and italic text), summary review metadata (left columns) and stakeholder gap priorities (red underlined numbering, right column). See Figure 4 for the key.**

| Theme | Database rows | Review metadata[1] | Categories of evidence level, combining 2022 review (base position) with updated 2025 review (confirmed or altered position) | | | | Gaps used in consultation with stakeholders |
|---|---|---|---|---|---|---|---|
| | | | Very strong | Strong | Moderate | Weak | |
| **Flooding** | 50-64 | C<br>C<br>C C C<br>C C C C C | | | **Slowing the flow; Reducing sediment delivery & siltation**<br>*RW type and placement; Model parameterization; Leaky barriers vs time* | *Floodplain RW for large scale, large events* | 12<br>13<br>14 |
| **Carbon** | 65-73 | C C C C<br>D D C C C | | | **C sequestration & storage**<br>*C inventories* | *GHG emissions with management* | 15<br>16 |
| **Clean air** | 74-79 | C<br>No more studies<br>D | | **Air pollution**<br>*Urban air pollution* → | | *RW designs into scaling via models; Pollution swapping air to water* | 17 |
| **Soils** | 80-84 | C D D C | | **Reducing soil loss** | | | 19 |
| | 85-93 | C D<br>A C | | | | **Improving soil health**<br>*UK evidence; Effects on mycorrhizae* | 18 |
| **Human health** | 94-99 | | | Exposure to river woodlands → | | *Psychological effects in Europe; Healthcare cost savings* | 27, 30, 29 |
| | 100-108 | C C C | | Cooling air → | | *Cooling effects of RW in urban blue-green infrastructure; tree characteristics green infrastructure; tree characteristics & cooling; wooded riparian zone effects in Scottish cities* | 28 |
| **Wild fish and angling** | 109-112 | No more studies<br>C C<br>No more studies | | Regulating local climate: shading → | | *Ground- & surface- water interactions; RW tree canopy type effects; RW dominated catchments vs other land covers* | 32 |
| | 113-114 | D D | | | **Providing food for fish** | | 31 |
| | 115-116 | D<br>No more studies | | | | **Fish habitat & large woody material**<br>*Effects on native UK fish and trophic interactions* | 32 |

**Table 4 continued. Mapping of evidence levels (black text, with horizontal arrows; combining 2025 review of specifics with previous 2022 review strength of evidence ratings), gaps area topics (blue and italic text), summary review metadata (left columns) and stakeholder gap priorities (red underlined numbering, right column). See Figure 4 for the key.**

| Theme | Database rows | Review metadata[1] | Very strong | Strong | Moderate | Weak | Gaps used in consultation with stakeholders |
|---|---|---|---|---|---|---|---|
| | | | *Categories of evidence level, combining 2022 review (base position) with updated 2025 review (confirmed or altered position)* | | | | |
| **Sustainable food production** | 118 | A | | Supporting pollination → | | *Woodland (not planted buffers) pollinator effects; Direct evidence for UK effects of RW at landscape scales* | 35 |
| | 119 | | | Providing shelter & shade for livestock → | | *Woodland benefits vs bank stabilisation conflicts; Upland/ lowland RW effects vs soil type & stock density* | <u>33</u> |
| | | No more studies | | | **Providing fodder for livestock** | *Nutritional and medicinal effects of RW grazing* | 34 |
| **Biomass** | 121-123 | C | | **Provision of biomass for energy** | | | 36, 37 |
| **Monitoring** | 124-128 | C C | | | **Strategies for robust monitoring over scales** | | |
| **Heritage** | 129-131 | No more studies<br>No more studies<br>No more studies | | | | **RW impacts on heritage sites; Community preferences & perceptions in RW applications; Acceptability of RW restoration to communities** | <u>41</u><br><u>42</u><br>43 |
| **Finance** | 132-133 | | | | **Evidence-based finance incentive schemes** | | |
| **Biodiversity** | 134-139 | C<br>No more studies<br><br>No more studies | | | **Non-native species interactions with RW; Effects of habitat fragmentation on RW; Plant pathogen impacts on RW expansion** | | <u>44</u><br><u>45</u><br><u>46</u><br>47 |

[1]Metadata for studies shows climate zone according to the Koppen-Geiger system, where C (temperate) shows data most transferable to UK conditions and A and D demotes other climate zones; [2]Pesticide load reduction was not originally placed in the summary table of the 2022 review (summary page iii) but was placed under moderate strength of evidence classification on P25 of the 2022 report; [3]Tree species adaptation to drought was not placed in the summary classification table in the 2022 review but was here considered weak evidence from the specific gap statement (see Table 6) that indicates an immature research level.

## 3.2 Overview of stakeholder results

Across the project we contacted more than 300 (295 directly and further through mailing lists and other networks) stakeholders of whom 115 participated in at least one stage of the engagement research. Key insights emerged about stakeholders' perceptions of evidence needs and their priorities in the context of the multiple challenges they face. Table 2 provides an overview of the number of different stakeholders engaged at each of the different stakeholder engagement stages.

Stakeholders across the multiple areas of RW expertise provided invaluable insights for prioritising future R&D. A number of stakeholders, particularly from the private sector, noted that they did not see a lack of evidence as a significant barrier to RW and considered that existing evidence is sufficient to enable decision making and practice. Other stakeholders did not feel confident formally discussing evidence needs (sometimes due to a perceived lack of familiarity with up-to-date formal evidence) and focused on challenges and barriers they encounter, still providing us with important points to link to evidence. Barriers highlighted by stakeholders through the project were:

- A lack of funding, incentives and other resources (such as staff and skills);
- Grazing impacts and ecological considerations: Deer and beavers;
- A lack of policy support for conservation with clearly identified areas for RW restoration and coverage targets;
- A lack of landowners' involvement in RW and social acceptance, communication and engagement with communities;
- A need for collaboration and knowledge sharing across sectors and some areas of evidence needs;
- Uncertainties relating to climate change vulnerability and resilience.

Recurring topics emerged across stakeholder groups that called for more evidence. The primary areas of interest were the effects of RW on flood and drought mitigation, RW effects on water quality and RW effects on biodiversity (see detailed results below). Linked to these evidence needs, overarching topics of importance emerged during stakeholder engagement. These included the need to integrate existing evidence into practical tools, develop sustainable finance mechanisms (noted especially in new gap 43 on *Evidence-based financial incentives*), improve monitoring practices (new gaps 38 on *Integration of evidence for applications*, and 39 on *Monitoring strategies*), and support policy development.

The results are presented in alignment with identified themes of benefits provided by RW. For each section we detail the gaps statements used for the survey and workshop and linked functional topics areas used for the update to the 2022 review. We then discuss the current state of evidence and the main patterns emerging from our stakeholder engagement.

## 3.3 Reduction in water pollution and interception of air pollution

### 3.3.1 Current state of evidence

For each topic being discussed the detailed gaps newly reviewed here appear in Table 5 with, for reference, the overall evidence classification from the 2022 review in Table 1. The 2022 review concluded that overall evidence for stabilising riverbanks is very strong (summary classification used across this function in Table 1) in terms of processes of stabilisation of soils by tree roots and strong in terms of the resulting effects on RW combating bank erosion and sediment supply. However, this evidence was found limited in terms of transfer of international evidence to UK and comparison with control (not wooded) catchments. Whilst the 2022 review showed strong evidence on RW capturing sediment in runoff, there were moderate strength classifications to the role of floodplain woodlands, especially for the UK and for the role of strategic RW planting in outcomes predicted by catchment-scale models. The gap statements here address aspects related to these as well as research needs specific to slope, soil effects and tree species. Findings from field experiments in Devon, England, by Dunn *et al.,* (2022) demonstrate that willow buffers and deciduous woodland buffers reduced suspended sediment delivery to watercourses by 44% and 30% respectively, further supporting the strong evidence that RW mitigate sediment delivery. Experiments were conducted on a site of 8° slope with seasonally waterlogged soils (clay loam). Cole *et al.,* (2020) provide further context on effective placement of riparian buffers in their riparian buffer management review, indicating buffer widths of 8-15 m adequate for fine and coarse sediment trapping on slopes <10° across different soils.

The 2022 review identified the gap related to predicting critical source areas and pollution hotspots in headwater catchments. Hirave *et al.,* (2021) using compound specific isotope analysis and a nested sampling regime (River Dee, Scotland) identified permanent grassland as the critical sediment source. Research in two Irish catchments (Thompson *et al.,* 2014) confirmed, using turbidity sensors, channel bank sources were dominant in one catchment and arable sources in another. Neither paper assessed RW specifically. Pollution hotspots are catchment-specific and a national study for Scotland has not been produced. Spatially distributed diffuse pollution models – for example SCIMAP applied by Perks *et al.,* (2017) in the River Esk catchment, England – could be used to identify critical source areas to inform pollution management and RW planting, but have not yet been used to do so.

Strong evidence regarding water nutrient pollution in the 2022 review related to reduction of nitrate leaching at the field scale (for buffers with trees relative to grass-only) and reduction of phosphorus loads (by processes of particulate P retention, with uncertain effects for dissolved phosphate). Despite overall strong evidence ranking in the 2022 review for RW actions affecting nitrogen and phosphorus pollution, gaps remained regarding catchment-scale nutrient exports relative to presence/absence of RW and for woodland buffer designs relative to reduction of dissolved reactive phosphorus. Weaver and Summers (2014) found in the Kalgan River Catchment, Western Australia, that riparian buffers were ineffective at soluble P retention for sandy soils where leaching and subsurface pathways of soluble P prevailed. The authors recommended investigating phosphorus transport pathways before buffer implementation. Difficulties in measuring the effectiveness of riparian woodland expansion on nutrient reduction at catchment scales are supported by the review by Hutchins *et al*., (2023). They found that urban forests across 14 catchments worldwide – including riparian tree planting – on average reduced total nitrogen by 16% and total phosphorus by 13% at the catchment scale; however, at large spatial scales it is difficult to identify confounding factors that may influence quantified reductions. The Hutchins *et al*., (2023) review also reported that leaf litter falling on impervious surfaces in urban areas can increase total phosphorus leaching to streams, which has implications for the 2022 review gap related to how woodland design and management affect pollution swapping. However, there was limited further research identified that explores pollution swapping processes involving trees in a non-urban context, or specifically for pesticides.

River woodland functions for mitigating excess algal growth and periphyton through shading were considered strong in the 2022 review using appropriate UK-relevant research; although flow, seasonality and nutrient level interactions were less considered. In this study, we found that Scottish-specific evidence and the use of modelling approaches such as the Quality Evaluation and Simulation Tool for River Systems (QUESTOR) remained a specific gap. Rising river temperatures in Scotland strengthen the need to investigate environmental change processes and implications for future algal or periphyton growth. The 2022 review identified strong evidence for the benefit of RW on capturing pesticides and herbicides, based on aerial trapping data. The identified gaps for woodland role in watercourse load reductions and pollution swapping associated with pesticide wash-off from leaves were considered here, with no further relevant literature found.

For the function of RW in trapping and infiltrating pathogens, determined as weak evidence in the 2022 review, Pettus *et al.,* (2015) evaluated 6,647 faecal coliform and e-coli samples from 532 small rivers in Oregon, USA, and found that riparian buffers had lower contributions of pollution compared to other land uses including grazing and urban use. The process aspects defined in the gap statement around rooting and infiltration trapping across soil types were not addressed in any literature and remain as gaps.

The 2022 review considered evidence specific to trees intercepting air pollutants strong, especially for urban woodland. Multiple gaps were identified covering species and location interactions in the urban context (barriers between roads and human receptors), model scaling towards effects of woodland networks and pollution swapping from air to water relating especially to designs comparing urban and farm woodland. Understanding of pollution swapping still needs to improve. A review on green infrastructure (Jones *et al.,* 2022) suggests trees intercept gaseous pollutants, including $NO_2$, $SO_2$ and PM2.5 fine particulates, associated with leaf area and roughness. In contrast, the Air Quality Expert Group, (Monks *et al.*, 2018) question the value of urban tree planting on pollutant removal, with trees being effective barriers only when close to pollutant sources or in scales of planting that were unrealistic to achieve.

We did not find quantified evidence of pollution swapping between water and air associated with RW, but one review identified the RZ-TRADEOFF model (Hassanzadeh *et al.,* 2019) used to predict the removal of nitrates and phosphates in subsurface flows, total phosphorus in overland flows and nitrous oxide, methane and carbon dioxide emission in riparian zones. This model could be used to address this gap in the Scottish context and help support RW implementation.

**Table 5. (a) Key aligned policies and strategies and (b) the thirteen detailed gap statements concerning water pollution and intercepting air pollution as taken from the 2022 review and the number of new additional papers covering gap specifics reviewed here.**

| Water pollution reduction and air pollution interception | (a) Key policies and strategies | |
|---|---|---|
| | • River Basin Management Plans (RBMP; Under Water Framework Directive WFD)<br>• Scotland's Water Environment Fund (WEF) | • UK Forestry Standard: Creating and Managing Riparian Woodland<br>• Woodland Water Code (WWC) |

| (b) Reviewed evidence topics | Detailed descriptions of specific gaps | n, papers |
|---|---|---|
| Clean water: Stabilising riverbanks | Further research needed on the design of riparian woodland buffers to maximise sediment retention capability (width and length for soil and slope combinations). This includes the right species mixes to reduce bank erosion at different locations in different catchment types in Scotland. Building the evidence base on bank stability and its impact on sediment loading within rivers in Scotland, with and without riparian woodland, will be beneficial. | 4 |
| | It is recommended that diffuse pollution buffers target a number of the main pollution hot spots in headwater catchments where collectively they can improve water quality. This includes focusing on critical source areas and protection zones based on understanding the main pollution delivery sources and pathways. For sediment pollution, this requires a further understanding of sediment sources in catchments throughout Scotland. It will be helpful to understand sediment source contributions with and without trees present. | 4 |
| Clean water: controlling nitrogen and phosphorus pollution | Empirical evidence of reduction of catchment nutrient exports from river woodland. | 1 |
| | Greater understanding of how woodland design and management affects pollution swapping. | 1 |
| | More evidence is needed to understand the effects of riparian buffer management options at the catchment scale to reduce nutrient and fine sediment pollution. Tools for understanding role of river woodland at catchment and sub catchment scales for benefits for nutrients and sediments are needed. | 5 |
| Clean water: controlling excessive algae and periphyton | The QUESTOR modelling study in River Ouse catchment in NE England is limited by field data but offers a potentially valuable tool to assess cost-effective methods of tackling effects of eutrophication. Further application of river quality models like QUESTOR in Scotland would be beneficial to understand excessive phytoplankton/algal bloom risks with climate change and how planting riparian shading in headwaters may help. | |
| Clean water: controlling pesticides | Greater understanding of woodland design and management affecting pollution swapping: the potential for pesticides to wash off leaves into the water course. | 0 |
| | Further understanding of pesticide load reductions in waterways in Scotland from land-use change to river woodland types. | 1 |
| Capturing sediment pollution | The application of modelling tools (such as SEDMAP) and or further development of modelling tools to assess the impact of strategic planting in upland catchments in Scotland is required. This includes root cohesion parameters in modelling tools. | 0 |
| Capturing pathogens | Further research is required to understand how physical trapping of pathogens via infiltration is influenced by tree roots and on different soil types and slope. | 2 |
| Clean air: intercept air pollution | The effectiveness of trees to capture air pollutants is strongly determined by species type and location and not much work has focused on appropriate design to integrate urban riparian woodlands into the urban landscape. | 3 |
| | Study to determine impacts from riparian tree species in a riparian woodland context next to watercourses and for modelling to integrate riparian woodland networks on a larger spatial scale is required. | 0 |
| | Research to transfer design for farm woodlands and urban woodlands to design of riparian woodlands, which takes account of the risks associated with pollution swapping from air to water is required. | 2 |

### 3.3.2 Stakeholder engagement

Through the prioritisation process, Gap 2, on *RW and riverbank stabilisation* was ranked as part of the four highest gaps by participants of the survey and the workshop and closely linked to Gap 3, (*RW and catchment nutrient pollution*) and Gap 5, (*RW and pesticide pollution*). Gaps 6 (*The effect of RW on pollution swapping in water pollution*), and 17 (*The effect of RW on pollution swapping in air pollution*) were ranked low in both research phases. Gap statements 4 (*The effect of RW shading on algal growth*), 7 (*The effect of RW on the transport of coarse sediment*) and 8 (*Tree rooting on water infiltration and physical particle trapping*) were ranked medium.

Stakeholders widely recognised RW role in improving water quality by reducing sediment loads, stabilising riverbanks, and regulating DOC levels. However, businesses and public sector representatives highlighted the need for better data to optimise tree placement and prevent unintended impacts. This connects to biodiversity and fisheries concerns, particularly the role of riparian trees in regulating water temperature for species like Atlantic salmon. Air quality benefits received little attention, though one expert noted the potential for pollution swapping between air and water in urban-riparian settings, linking this to human health considerations. A major gap identified was the lack of long-term monitoring and baseline data, with calls for integrating ecological, chemical, and hydrological perspectives to fully assess RW benefits. Stakeholders emphasised the need for both localised studies and broader-scale research to track pollutants, temperature, and nutrient cycling before and after woodland establishment.

While some believed sedimentation and nutrient management were well understood, others called for more evidence on pollution swapping, DOC impacts on drinking water, and pesticide presence in riparian systems. Additionally, while tree shading is generally seen as beneficial for water quality, concerns were raised about potential trade-offs, such as reduced food source for invertebrates which could then reduce food source for juvenile salmonids.

#### Specific sectors interests and needs for further evidence.

**Water industry:** The water industry seeks information relating to the effect of RW on land stabilisation to reduce erosion/runoff and their effect on upstream cooling to reduce water temperature and reduce risk of algal blooms. For example, what scale of RW is necessary in achieve specific benefits, on algal bloom and runoff. Evidence on phytoremediation's role in addressing nutrient and chemical pollution could support broader catchment management strategies. In the context of drinking water policy, improved understanding of how riparian planting influences DOC levels, water pH, and potential chemical runoff is crucial, particularly for private water supplies. Further, the impact of pesticides and chemical treatments used in establishing RW remains a regulatory challenge.

**Water-using industries:** These private sector industries expressed interest in RW management to safeguard water quality. They emphasise the need for better baseline data and long-term monitoring to support their involvement.

**Urban planning and developers:** Although we did not engage with urban planners, other stakeholders in the public sector underlined that the sector may benefit from evidence on designing blue-green infrastructure that integrates RW to maximise air quality and cooling benefits. Evidence on species-specific air pollution mitigation and the risks of pollution swapping in urban areas is needed. The recent SNAP 3 states in its Outcome one – Objective 1 its commitment to enhancing Blue-Green infrastructures.

**Fisheries:** Understanding the role of RW in maintaining optimal thermal regimes and supporting aquatic biodiversity, especially for economically and ecologically important fish species, remains a priority.

**Environmental agencies:** River woodlands' mitigating effects on water and air pollution align with key policy frameworks and regulatory priorities. Diffuse pollution remains the primary pressure on water environments, as identified in River Basin Management Plans (RBMP), with physical alterations to rivers ranking third. Regulatory bodies already recognise the potential of RW to reduce runoff, enhance water quality, and contribute to the recovery of river morphology; there is growing interest in their impact on pesticide retention, nutrient budgets, DOC levels, and pH fluctuations, highlighting needs for both improved monitoring and predictive tools to inform management decisions.

From a policy development perspective, small headwater streams remain underrepresented in national water quality assessments, despite their substantial influence on downstream receiving waters. There is an increasing focus on integrating riparian woodland restoration within these smaller catchments to enhance water quality outcomes. However, evidence gaps persist regarding the role of different tree species in erosion prevention, the effectiveness of phytoremediation for nutrient and chemical pollution control, and the broader implications of riparian woodland expansion for drinking water resources.

**Forestry:** The UK Forestry Standard: Creating and Managing Riparian Woodland emphasises the need to assess riparian woodlands' effectiveness in removing microbial pathogens from surface runoff, particularly in agricultural landscapes where contamination from livestock threatens drinking and bathing waters. While riparian woodland buffers are expected to provide some reduction in pathogen load, especially when infiltration is enhanced through strategic planting, further research is needed to quantify these effects. Additionally, the exclusion of livestock through fencing has been identified as a significant mitigation measure to reduce contamination risks.

There is clearly overlap in the topics that are relevant to different sectors. For example, understanding how riparian planting influences DOC, water pH and chemical runoff, is relevant both to achieving goals for river basin management and drinking water. Addressing these evidence needs, and updating policy development to reflect what is already known, requires collaboration between policymakers, researchers, and land managers to refine guidance, develop catchment-scale pollution mapping tools, and explore options for integrating nutrient budgets into initiatives like the Woodland Water Code (WWC).

### 3.3.3 Synthesis between stakeholder evidence perceptions, needs and current state of evidence on pollution of water and air

Synergies between stakeholder perceptions and the current state of evidence are evident in the acceptance of the current state of knowledge regarding RW benefits for sedimentation and nutrients (Gap 2 on *RW and riverbank stabilisation*, 3 on *RW and catchment nutrient pollution*, 7 on *RW and catchment nutrient pollution*). There is strong evidence that RW increase bank stability and mainly buffer nutrient pollution. There is less evidence for RW role in buffering phosphorus pollution in catchments where subsurface phosphorus pathways are dominant, however, this gap compliments the call for the right tree, in the right place from stakeholders, and the limited evidence concerning pollution swapping (Gaps *6 The effect of RW on pollution swapping in water pollution* and *17 The effect of RW on pollution swapping in air pollution*).

Further synergies are identified where key evidence gaps remain, mainly concerning the role of RW in mitigating pesticides, pathogens and the potential effects of tree shading in mitigating excessive algae and periphyton (Gap *4 The effect of RW shading on algal growth*, *5 RW and pesticide pollution, 8 Tree rooting on water infiltration and physical particle trapping*). For the latter of the mentioned gaps, it was interesting that stakeholders mentioned the potential negative impact of tree shading on invertebrate populations, as this was not included as an evidence gap in the 2022 review. However, evidence in two catchments in Germany (Demars *et al.,* 2014) suggests shading may reduce species abundance. Here, the Creating and Managing Riparian Woodland guidelines (Forest Research, 2024) are relevant (water 32 states: *"Aim for a mix of shaded and lightly shaded habitat within the riparian zone, guided by local objectives and the requirements of priority species."*).

Another gap identified by stakeholders is the presence of DOC at levels causing problems for drinking water treatment. Due to long-standing applied research with academia and Scottish Water on this, there is good process knowledge, but RW specific trials should be adopted if not already commenced.

There was agreement between the evidence and stakeholder desire for improved, localised, understanding of RW benefits and the conditions in which their benefits can be best realised. The 2022 review raises the need to understand the impact of RW implementation on catchment-scale nutrient exports, however, our evidence highlights the difficulty in measuring and attributing benefits at large scales. At the local scale, future studies should provide detailed information on site and species-specific information to help solidify the conditions for right tree, right place, realise benefits and support future implementation.

Stakeholders identified needs for a better understanding of pollution sources and pathways (Gap 1, *Ecological and chemical status of headwaters*), where the updated review show limited additional research in this area. We present a number of studies using a variety of tools that track and attribute sediment sources, while tools, such as Source Apportionment GIS tools (SAGIS) can be used to apportion loads and concentrations to multiple chemicals (Comber *et al.,* 2013).

The benefits and limitations of RW on bank stabilisation and nutrient buffering are supported by strong evidence that is recognised by stakeholders. Research should be prioritised to understand RW impacts on pesticides, pathogens and DOC, as well as the potential for pollution swapping. Investigations should be prioritised at the local scale, integrating ecological, chemical, and hydrological perspectives to realise benefits and support future woodland implementation. Data collation and consistency in observations/monitoring would help to facilitate modelling towards effects for larger-scale waterbodies. Additional monitoring and RW experiments on headwaters would help fill the gap associated with lack of national regulatory surveillance monitoring for that scale. Challenges remain of scaling small catchment findings of woodland effects to the larger waterbodies, where negative effects for ecology and human health and recreation are manifest and well recognised as a priority by stakeholders. Investment towards woodland implementation could be facilitated by metrics and impacts across water pollutants.

## 3.4 Water stress and drought adaptation

### 3.4.1 Current state of evidence

For each topic being discussed the eight detailed gaps newly reviewed here appear in Table 6. The 2022 review concluded there was moderate evidence related to the RW function of modifying local climate, and weak evidence for buffering low flows and tree species adaptation to drought (Table 1).

The functions addressed under this topic in the 2022 review concerned the ability for RW in modifying local climates via shading and cooling air and hydraulic lifting. Evidence for biophysical

**Table 6. (a) Key aligned policies and strategies and (b) the eight detailed gap statements concerning drought mitigation and adaptation as taken from the 2022 review and the number of new additional papers covering gap specifics reviewed here.**

<table>
<tr><td rowspan="12">Water stress - Drought mitigation and adaptation</td><td colspan="3">(a) Key policies and strategies</td></tr>
<tr><td colspan="2">• Scotland's Water Scarcity Plan<br>• Scottish National Adaptation Plan (SNAP3)<br>• National Planning Framework 4 (NPF4) and Local Environmental Planning</td><td>• Scottish Biodiversity Strategy (SBS)<br>• Water Framework Directive (WFD)<br>• River Basin Management Plans (RBMP)</td></tr>
<tr><td>(b) Reviewed evidence topics</td><td>Detailed descriptions of specific gaps</td><td>n, papers</td></tr>
<tr><td rowspan="2">Modifying local climate: shading, air cooling, hydraulic lifting</td><td>There is a moderate level of evidence that hydraulic lifting can buffer plants against water stress during dry periods on alluvial soils of semi-natural floodplain woodland types in Europe.</td><td>2</td></tr>
<tr><td>Review work and field research on quantifying the benefits of different tree species on maintaining soil moisture content on different types of soils. Improve understanding of how hydraulic lifting and bioirrigation processes work in the UK to provide the right advice to farmers on how to incorporate these processes into agroforestry designs.</td><td>1</td></tr>
<tr><td rowspan="5">Maintaining water supplies</td><td>More research is required to understand the differences in evapotranspiration rates and water use of different tree species suitable for planting native woodlands in the UK, particularly in Scotland. This includes understanding other factors which affect water use including local climate, soil type, geology and woodland design and management.</td><td>4</td></tr>
<tr><td>Development and improvement of hydrological models to include parameters on wider range of Scottish native tree species and soil types.</td><td>2</td></tr>
<tr><td>There is a need to understand the impact on private and public water supplies and appropriate buffer widths and tree species that can be planted.</td><td>0</td></tr>
<tr><td>National-scale risk-based tool to evaluate the vulnerability of water supplies to drought to target appropriate mitigation measures including planting.</td><td>1</td></tr>
<tr><td>Better understanding of the role of natural floodplain woodland in maintaining river low flows in the UK.</td><td>2</td></tr>
<tr><td>Tree species adaption to drought</td><td>Research to understand if riparian and floodplain tree species can adapt to drought in Scotland.</td><td>0</td></tr>
</table>

processes of shading, maintaining humidity from the river, reducing evapotranspiration and soil drying was classified strong. Hydraulic lifting effects buffering water stress on alluvial floodplain soils in Europe was considered moderate, whilst effects from silvopastoral practices were considered weak. No studies addressing the specific gap relating to the role of hydraulic lifting in buffering against water stress during dry periods on alluvial soils of semi-natural floodplain woodland types, or the effects of different RW type on local soil moisture content were identified. Although not for RW specifically, Geris *et al.,* (2015) found soil properties had a greater influence on soil water content than vegetation when comparing forested and non-forested sites in a small headwater catchment of the River Dee. In a recent CREW study exploring the links between trees and water availability in a Scottish context, Geris *et al.,* (2024) described more broadly that the effects of tree planting on water availability can vary widely based on a complex set of inter-related factors, such as timing, spatial orientation, extent of planting, tree species, and landscape characteristics, including previous land use.

The 2022 review described a lack of knowledge on the potential role of RW in maintaining water yields and affecting low flows, and this remains. A body of aligned work carried out in arid regions was considered not relevant to UK. However, Beuchel *et al.,* (2022) modelled the impacts of catchment-wide afforestation (not riparian-specific) across twelve diverse UK catchments and predicted a greater prevalence of low streamflow. Similarly, Fennell *et al.,* (2023a) predicted greater low flow prevalence modelled for a 1 $km^2$ Speyside headwater catchment for different tree planting scenarios, including riparian planting of coniferous species. Neither study involved observational data on RW, nor did they consider the potential effect of other physical processes including shading, which could contribute to cooling and have associated effects on RW microclimates. Further, no studies were identified that specifically investigate the impacts of RW on public or private water supplies. A national study of future predictions of drought and water scarcity in Scotland by Glendell *et al.,* (2024) was identified, however, the implications to water supplies are not measured and tree planting mitigation was not considered.

Evidence of how riparian and floodplain tree species would adapt to drought in Scotland was not classified in terms of evidence strength in the 2022 review, but we here base the ranking of weak on the gap statement taken from the 2022 review. The Terrestrial Regional Ecosystem Exchange Simulator (TREES) model described by Mackay *et al.,* (2015) shows promise in addressing this gap. The TREES model links photosynthesis and carbon allocation to soil-plant hydraulics and canopy processes to help measure tree response to drought. The model was applied by Tai *et al.,* (2018) to understand the susceptibility of RW trees to drought mortality within a 3 km river corridor in Oldman River Valley, Canada. Our evidence review didn't find similar studies in Scotland. However, the TREES model could be applied to understand the adaptive capacities of RW tree species in Scotland.

### 3.4.2 Stakeholder engagement

Gap 9 on *RW effect on river flow during dry periods* was ranked among the top 5 priorities during both the survey and the workshop. Gap 11 on Drought tolerance of tree species was consistently mentioned as high priority while Gap 10 on *RW effect on soil moisture* was maintained in the medium priority cluster.

Stakeholders widely recognised RW role in drought resilience, particularly in enhancing water retention, infiltration, and recharge. RW was often discussed alongside flooding, highlighting its multiple co-benefits for water management, biodiversity, and climate resilience. However, concerns were raised about potential trade-offs, such as tree water uptake reducing stream inflows. Improved hydrological modelling was identified as a key research need to quantify these effects and better understand RW interactions with soil moisture and river flow during dry periods.

Differences emerged regarding evidence transferability. Some stakeholders felt existing research on drought-tolerant tree species was sufficient, while others emphasised the need for Scotland-specific data. There was also debate on research scale — some advocated for localised studies on tree impacts in specific catchments, while others called for large-scale modelling to assess broader hydrological effects.

### Specific sectors interests and needs for further evidence

**Agriculture:** Concerns centred on economic implications for farmers, such as soil health, animal welfare, and productivity under drought conditions. Evidence needs/interests include the role of trees in mitigating water shortages for crops and livestock.

**Public sector (environmental agencies), scientists, others:** Focus on evidence for long-term resilience and biodiversity gains, including the adaptive capacity of tree species to drought in Scotland. Balancing conservation goals, such as biodiversity enhancement and water scarcity mitigation, was identified as a potential source of tension.

**Other sectors with potential interest:** Though not explicitly discussed in the workshops, drought resilience may be a key issue for water-dependent industries, including whisky production and other businesses, highlighting the need for broader knowledge exchange.

**Policy:** The role of RW in mitigating water scarcity is a significant policy interest, particularly as climate change increases pressures on agriculture and water resources. Funding and resource allocation were identified as significant barriers to scaling up nature-based solutions. Policies such as the *SBS Delivery Plan* required specific evidence to guide RW placement for drought adaptation, through improved mapping tools and environmental impact assessments (EIAs). Policy stakeholders needed better understanding of hydrological impacts of RW improving resilience to drought, rationalising evapotranspiration reducing water availability, against enhancement of groundwater recharge during wetter months. SNAP3 calls for research on refining water scarcity monitoring and improving forecasting models. Ongoing work through the RESAS Strategic Research Programme includes assessing how natural flood management techniques (e.g., woodland buffers) can help retain water in the landscape and mitigate the effects of dry periods. Scotland's Water Scarcity Plan requires integration of RW management into water resources planning, including managing abstraction licenses and supporting farmers in adapting to drought conditions. Understanding the resilience of different tree species to water scarcity will be crucial in ensuring RW contribute effectively to long-term water security.

### 3.4.3 Synthesis between stakeholder evidence perceptions, needs and current state of research on drought mitigation and adaptation

While stakeholders identified a high-priority need for evidence on the role of RW during drought, especially the effects of RW on low flows, our latest evidence review and the findings from the 2022 review indicate a general lack of drought related evidence (including topics such as hydraulic lifting and biorrigation). There is no clear empirical or modelled evidence for whether RW in Scotland could either help mitigate or even exacerbate low flows and water availability more generally during drought conditions. The trade-offs between (multiple) benefits and potential unintended consequences were also recognised by stakeholders as a key issue. Whilst modelling studies suggested that low flows could decrease as a result of establishing RW, their lack of process representation and observational data from Scottish RW sites results in these effects being highly uncertain. The need for more effective modelling studies was also underlined by stakeholders.

Understanding interactions between RW and drought conditions was identified as high priority due to the current lack of evidence. Research should focus on potential trade-offs between effects that increase drought mitigation versus those that could contribute to drought issues. The role of tree and site-specific characteristics would be important to investigate in this context. There is a need for more holistic research approaches that explore RW addressing multiple benefit areas alongside drought adaptation, including biodiversity and flood management.

## 3.5 Flood risk alleviation

### 3.5.1 Current state of evidence

The specific gaps reviewed appear in Table 7 and the original evidence strength in Table 1. As a form of natural flood management, there is the potential for woodlands to mitigate flood risk by delaying flood peaks, both temporally and spatially (Cooper *et al.,* 2021). Specifically for riparian and floodplain woodlands, including in-stream woody materials (i.e. leaky barriers), the 2022 review indicated that there was moderate evidence available for their role in slowing the flow for flood risk alleviation. Evidence for these benefits is available for smaller scale catchments or tributaries, and at least in the mainstream riparian setting, but low confidence remains for the role in flood mitigation at larger catchment scales and during larger flood events

(Ngai *et al.,* 2017; Gaps *12 RW effect on flood risk and 14 Leaky barriers on flood mitigation*). This theme is consistently present in the 2025 update of the Working with Natural Processes Evidence Directory (ED) (Pearson *et al.,* 2025), which includes both riparian and floodplain woodlands, with confidence levels unchanged from the 2017 version (Ngai *et al.,* 2017). In some cases, more specific evidence levels have been lowered on two occasions and increased on one occasion. Overall, the ED update aligns with our findings, indicating a moderate level of evidence. This generally applies to leaky barriers as well, with most gaps remaining unchanged, except for maintenance, which was lowered. The review aligns with our findings of an increasing body of literature, although research gaps persist. Additionally, for leaky barriers, we have identified Scottish studies not included in the 2025 ED literature review database (e.g., Roberts *et al.,* 2024; Fennell *et al.,* 2023b).

Modelling studies at larger scales are increasingly able to provide useful insights. Lavers *et al.,* (2022) revealed that flood peak attenuation from natural flood management scenarios diminished with catchment scale, but even at the largest hydrological scale (large events at 187 $km^2$), delays in time-to-peak were noted. However, this work looked at the combined effect of multiple measures, so it was not possible to disentangle the effect of RW as a single measure. In their reviews of modelling natural flood management, Hill *et al.*, (2023) and Hankin *et al.,* (2017) make recommendations for best-practice, including for RW, but they do not focus on improving parameterisation of RW as a specific measure. Knowledge from modelling studies at larger scales therefore remains limited in terms of data-based parameterisation and calibration.

There is also a need to better understand how specific details of RW, such as tree type and placement, affect flood risks. Monger (2022) found that riparian zone planting maximized the effectiveness of natural flood management compared to random placement across the catchment. However, this study didn't consider tree type or larger catchment scales. Singh *et al.,* (2024) provided insights from a lab experiment on planting parameters (e.g., tree density, orientation, spacing), but these have yet to be tested in real-world scenarios.

Since 2022, several studies have explored the role of leaky barriers in flood risk alleviation (e.g., Fennell *et al.,* 2023b; Follett *et al.,* 2024; Roberts *et al.,* 2024; van Leeuwen *et al.,* 2024). These studies, though based on small-scale, short-term experiments, show that leaky barriers can reduce and delay peak flows. Their effectiveness depends on construction aspects, available storage capacity, and placement. The effects on delaying or attenuating flood peaks also appear to decrease with increasingly larger events (Follett *et al.,* 2024). While Roberts *et al.,* (2024) revealed that age (length of time in situ) may also affect the functioning of leaky barriers, more evidence from long-term experiments is needed to really understand how their role may change with time. Since 2022, UK research has focused on human-made barriers, with fewer studies on naturally occurring fallen wood's impact on flood risk.

**Table 7. (a) Key aligned policies and strategies and (b) the four detailed gap statements concerning flood risk alleviation as taken from the 2022 review and the number of new additional papers covering gap specifics reviewed here.**

| **Flood mitigation** | **(a) Key policies and strategies** | | |
|---|---|---|---|
| | • National Planning Framework 4 (NPF4) and Local Environmental Planning<br>• Flood Resilience Strategy (SNFRS)<br>• Flood Risk Management Planning (FRMP) | • Scottish National Adaptation Plan (SNAP3)<br>• The UK Forestry Standard: The Governments' Approach to Sustainable Forest Management | |
| | **(b) Reviewed evidence topics** | **Detailed descriptions of specific gaps** | **n, papers** |
| | Slowing the flow | Understanding how the type of riparian woodland, its placement in the catchment and the catchment's size affects its flood risk impact. | 3 |
| | | More model parameter ranges are needed to represent woodland hydrological processes, and properly assess flood risk impacts and to test the upscaling of these to the catchment level. | 2 |
| | | Better understanding of the impact of floodplain woodlands during larger flood events across a range of spatial scales and to improve flood modelling. | 5 |
| | Reducing coarse sediment transport and channel siltation | Better understanding the effectiveness of leaky barriers and large woody material at mitigating flood peaks at larger catchment scales, and for larger flood events, including design and construction aspects. | 5 |

In relation to the evidence classification for RW reducing coarse sediment delivery (Tables 1, 4) during high flows this is moderate on the basis that the biophysical processes are understood, but there are limitations for evidence on strategic RW planting (apart from modelling) and placed deadwood (e.g. log jams) effectiveness. Although the literature against these topics is growing recently the specifics of the gaps are not yet adequately addressed.

### 3.5.2 Stakeholder engagement

The topic of flood risk management emerged as a high priority across all the engagement phases and was of interest to nearly all stakeholders. Gap 12 (*RW effect on flood risk*) emerged as a top priority from both the survey and workshop. Stakeholders emphasised the need to optimise woodland placement and assess its practical benefits for flood mitigation. Gap 14 (*Leaky barriers effect on sediment load*) was also ranked highly while Gap 13 (*Leaky barriers on flood mitigation*) was viewed as less critical in the survey but ranked highly during the subsequent workshop.

Stakeholders expressed a strong need for evidence and tools to assess RW's feasibility and cost-effectiveness in reducing flood risks. There were consistent calls for better data to justify funding and encourage adoption, as well as improved modelling and mapping tools to identify optimal RW placement. Existing evidence from other regions (e.g., England) was often cited, but its applicability to Scotland remained uncertain. Specific gaps or disconnects in mapping tools and strategies for strategic placement, as well as in how Environmental Impact Assessments (EIAs) attend to RW, could hinder incorporation of RW into existing flood management strategies. Stakeholders also sought information on how RW flood management benefits intersect with other effects, such as biodiversity gains, carbon sequestration, and potential operational risks like culvert blockages. The recent WWNP update (Pearson *et al.,* 2025) has included wider benefits of RW from a Natural Flood Management perspective.

Long-term monitoring was a major concern, with calls for frameworks to track flood resilience, biodiversity, and socio-economic outcomes over time. Stakeholders emphasised the challenge of securing funding for projects with delayed benefits and stressed the importance of evidence-based community engagement to build trust. Debates emerged over the certainty of RW flood reduction effects, with key knowledge gaps identified around placement, topography, and soil type. While some stakeholders saw leaky barriers as beneficial for floodplain reconnection, others raised concerns about potential infrastructure blockages and downstream flooding risks.

#### Specific sectors interests and needs for further evidence

**Private sector and utilities:** These stakeholders sought evidence on specific benefits of RW (e.g., flood risk reduction and biodiversity) and emphasised economic feasibility. They highlighted the need for precise, locally relevant data to guide tree placement for optimal outcomes. Very localised effects (e.g. on business infrastructure) may be required to justify involvement.

**Land-managers** were not so much focused on evidence gaps, rather barriers such as financial risks, cultural hesitancy, and difficulties and risks of implementation (e.g., potential tree loss during floods) were prominent concerns. Farmers called for better communication of existing evidence and stronger policy incentives.

**Restoration practitioners** prioritised pre-project baseline data and site-specific evidence on planting conditions, species compatibility, to maximise positive outcomes including for floods.

**Policy stakeholders** emphasised the need for more comprehensive evidence regarding the operational effects of riparian tree planting on flood risk management. Key concerns raised included the potential for increased tree cover to block culverts or cause fallen timber to obstruct streams, which could exacerbate flooding. Participants also stressed the importance of improving field-scale mapping tools, including more consistency between tools, to guide the strategic placement of RW, as well as integrating these trees into broader NFM strategies. Policy makers sought improved communication of existing evidence and decision support tools (e.g., to help target overland flow pathways at the field scale). Cross-policy integration is also required. Improving the understanding of how specific tree species perform in flood-prone areas will be essential for long-term resilience and effective adaptation to flood events. This call for better evidence aligns with the UK Forestry Standard's guidelines (The UK Forestry Standard and The Governments' Approach to Sustainable Forest Management), which advocate for woodland creation and management to mitigate flood risks.

It also highlights the need for careful management of forest drainage, particularly in large-scale forest felling projects, to prevent exacerbating flood risks.

### 3.5.3 Synthesis between stakeholder evidence perceptions, needs and current state of research on flood risk mitigation

Overall, both our review of the literature and stakeholder engagement highlight a need for improving the evidence base on how RW mitigate flood peaks at larger scales. There is a particular need for more empirical studies that focus on the design and placement of RW by themselves, to understand their multiple effects over time. These can be informed by - and then later inform - current modelling. The updated review shows that evidence is still required across RW types and also to assess the temporal variability as RW establish. Linked to this, better model processes understanding and parameterisation is still required which can then aid with understanding processes at scale.

Stakeholders highlight a need for site-specific predictions arising from supporting RW for example for a business premises, or a farm landholding, helping to understand and justify supporting RW. However, this does not contradict the need to develop more catchment-scale understanding which is lacking from current evidence. Careful communication to manage expectations of human-made leaky barriers is needed and how this translates to natural wood in streams. Although RW take time to establish, measures such as leaky barriers can be instantaneous in their effectiveness, so can be attractive. However, more studies are required on the correct design and placement of leaky barriers to ensure they minimise any negative consequences (i.e. not blocking downstream culverts).

In summary, the strength of evidence for RW remains unchanged since 2022, though it has improved for leaky barriers. This broadly aligns with the findings of the 2025 Working with Natural Processes Evidence Directory update. A lack of critical details hinders confidence in their use for flood risk mitigation. More research is needed on design and placement, especially for larger scales and events. Empirical studies and improved modelling could enhance process understanding. Further research on leaky barriers would help refine guidance and address stakeholder concerns. Long-term monitoring is essential, and learning from UK and international case studies can provide valuable insights for effective flood risk management.

## 3.6 River woodland carbon storage

### 3.6.1 Current state of evidence

The specific gaps reviewed appear in Table 8 and the original evidence strength in Table 1. Evidence related to the benefits of RW for carbon sequestration and storage were scored as moderate in the 2022 review, since quantification of positive effects for Scotland across river and RW types were found limited, with predominance of study data from the U.S. However, the conceptual study by Sutfin *et al.,* 2015 (considered in the 2022 review) suggests riparian and floodplain zones can have greater area-based C-storage than upland areas, especially unconfined valleys in wet and cool regions. No further evidence was identified to address the identified gap on C-storage comparing wooded vs non-wooded zones along different Scottish rivers. European temperate zone primary studies quantified C-storage in riparian and floodplain woodland across different river systems including woodland compositions, age and soil types (Graft-Rosenfellner *et al*., 2016, Shupe *et al*.,

**Table 8. (a) Key aligned policies and strategies and (b) the two detailed gap statements concerning carbon storage as taken from the 2022 review and the number of new additional papers covering gap specifics reviewed here.**

| Flood mitigation | (a) Key policies and strategies | | |
|---|---|---|---|
| | • Climate Change Act (2009)<br>• Scotland's Forestry Strategy (SFS) | • Woodland Carbon Code (WWC)<br>• UK Forestry Standard (UKFS) | |
| | **(b) Reviewed evidence topics** | **Detailed descriptions of specific gaps** | **n, papers** |
| | Carbon sequestration and storage | Further research and field data to understand carbon storage on different types of river systems in Scotland to include carbon stored in the trees, soils and large woody material. | 5 |
| | | Studies considering non-carbon Green House Gas emission impacts from changing land-use involving RW creation Vs open habitats such as bogs/wetlands. | 5 |

2021, 2022, Saklaurs *et al*., 2022). However, these did not partition standing-, dead- wood and soil C-storage; hence this remains an evidence gap. Such limited UK-specific evidence on differing environmental compartments of C-storage under riparian woodland types has contributed to lack of specific consideration in the development of the UK Woodland Carbon Code (WCC).

Relevant primary data (often from Canada) were identified to address the specific gap on RW restoration and creation effects on greenhouse gas (GHG) emissions across land use and soil conditions. De Carlo *et al.,* (2019) compared nitrous oxide ($N_2O$) emission between rehabilitated and undisturbed riparian forests in the Nith River Catchment, Canada and found stronger influence of soil conditions and seasonality than vegetation type. Silverthorn & Richardson (2021) measured soil-atmosphere exchanges of carbon dioxide ($CO_2$), methane ($CH_4$) and $N_2O$ fluxes in headwater riparian zones in Canada. Fluxes in $CO_2$ and $N_2O$ were mainly driven by soil temperature, while fluxes of $CH_4$ were driven by soil moisture. For $CH_4$ fluxes, Baskerville *et al.,* (2021), examined emissions across different Canadian riparian vegetation types, where emissions were greatest in an undisturbed natural deciduous riparian forest and lowest in grass riparian zones, but the opposite for $CO_2$ emissions. Soil organic carbon, soil moisture and photosynthetic photon flux density were key predictors of $CH_4$ emissions across the study. Our evidence suggests that there is no common evidence trend across different GHGs, and the influence of vegetation and soil dynamics influence GHGs differently. There were no comparisons between changes in land cover, including bogs and wetlands, relative to woodland restoration, creation or presence.

### 3.6.2 Stakeholder engagement

Stakeholders identified Gap 16 on *RW effect on GhG*, as a high-priority topic. This prioritisation was accompanied by the specific consideration of potential emissions resulting from soil disturbance during planting. In contrast, Gap 15 on *RW and carbon storage*, was regarded as a medium-priority issue across the various phases of engagement.

Stakeholders recognised carbon sequestration as a key benefit of RW but emphasised the need for an integrated approach that balances carbon storage with biodiversity and other ecosystem services. There were strong calls for metrics that combine carbon, biodiversity, and nutrient benefits to avoid unintended ecological trade-offs. Tools were also needed to ensure trees are planted in the right places for maximum multi-benefit outcomes.

There was significant interest in using carbon credits and biodiversity markets to fund RW restoration, but stakeholders highlighted concerns about long-term monitoring to verify benefits. Some landowners saw potential financial incentives in carbon credits but were cautious due to fears of "greenwashing," complex contracts, and limited government oversight.

#### Specific sectors interests and needs for further evidence

**Environmental sector:** Concerns and need for evidence on RW planting appropriateness in wetlands and other habitats, accounting for GHG trade-offs.

**Agricultural sector:** Farmers, would welcome evidence on the long-term benefits of RW on farm resilience and profitability. Some expressed scepticism about private finance mechanisms, stressing the need for greater transparency and regulatory safeguards.

**Private sector and cross sector:** Key beneficiaries of RW initiatives include purchasers of carbon credits and organizations aiming to offset or inset carbon emissions. For example, woodlands can contribute to Net Zero goals of various organisations by reducing operational intensity and associated carbon costs.

**Policy:** Evidence needs included understanding the role of RW in carbon sequestration and the potential trade-offs between climate benefits and GHG footprints. Policy required evidence quantifying cumulative net C-storage over longer timescales and to understand and act on concerns for unintended consequences of tree planting in certain landscapes, particularly wetlands, where increased GHG emissions may outweigh sequestration benefits. Specific requirements were for: (i) biogeographical strategies for climate-resilient tree species, balancing long-term carbon storage benefits with minimised risk of woodland loss due to climate extremes, and (ii) datasets and mapping tools optimising RW planting, ensuring carbon benefits align with biodiversity, water management, and land-use objectives.

Multiple objectives aspects noted above are covered by the WCC (WCC, 2022). The WCC was noted as having inherent complexity and profitability concerns whilst giving an example of robust ecosystem marketing approach. Stakeholders emphasised the role of regulation and planning in standardising such nature finance mechanisms, such as WCC. It was recognised that WCC doesn't address woodland resilience, a gap that remains in current monitoring of woodland schemes, although the UK Forestry Standard (UKFS) dictates woodland projects must conduct risk assessments to ensure trees are appropriately selected for site and climate conditions. Strengthening the evidence base on woodland resilience, particularly in the context of carbon sequestration trade-offs in different landscapes (e.g. wetlands, uplands), will be critical for aligning carbon-focused policies with broader adaptation strategies.

### 3.6.3 Synthesis between stakeholder evidence perceptions, needs and current state of research on carbon storage

Our literature review supports the positive views stakeholders have on the role of RW in storing and sequestering carbon. The evidence and stakeholder opinion also agree that if RW planting is solely for carbon storage, trade-offs with other GHG emissions may be missed, as demonstrated by the evidence of increased methane emissions from deciduous riparian zones compared to herbaceous grass riparian zones. Site-specific factors should be considered for restoration efforts to reduce trade-offs. Beyond the trade-offs between different GHGs, stakeholders encouraged the use of a holistic metric to inform RW restoration which combines multiple different metrics to assess benefits.

Newly reviewed evidence on GHGs were considered to weakly address the GHG gap and moderately the C inventory gaps. River woodland restoration has potential benefits for carbon storage and sequestration. However, detailed inventories of standing wood, dead wood and in-channel wood are yet to be quantified for UK conditions. Scale and and future change considerations will need to be addressed by predictive modeling to inform strategy documents like the WCC. A greater understanding of GHG emissions across different RW types and the factors influencing GHG emissions is required to inform appropriate planting and restoration efforts. Further research is needed to integrate the existing WCC framework across climate, pollution, soil protection and ecosystem service benefits.

## 3.7 Soil health

### 3.7.1 Current state of evidence

The specific gaps reviewed appear in Table 9 and the original evidence strength in Table 1. The 2022 review considered the function 'reducing soil loss' as strongly evidenced as this brings together well-researched aspects of RW processes in addressing erosion and runoff retention across benefits areas. Whereas 'improving soil health' was considered a weak area of evidence as research on benefits addressed generally in literature for soil structure, carbon and biodiversity are not yet specific to native RW. We support this, with caveats that soil loss considering economic aspects (as a specific focus of the earlier review) is moderate-strong as UK cost-effectiveness across bank and surface runoff erosion cannot readily be drawn from the wider pool of global literature. Also, soil health is a rapidly developing topic with global research of relevance to the UK; whilst it is developing it is timely to build knowledge for UK conditions.

Global literature showed recent papers covered functions of soil chemical, physical, biodiversity, microbial, structural and nutrient cycling functions (n=5), and the role of mycorrhiza in riparian restoration by tree planting (n=4). Soil health papers selected covered global (Brazil, Canada) primary studies and non-place-based framework papers and show limitations in available studies directly transferable to UK climate and land management. Udawatta *et al.,* (2022) generalised agroforestry benefits without specific riparian context, but a review by Inandmar *et al.,* (2023) targeting soil health indicators for river and floodplain restoration, usefully recommended ten indicators. Ofusu *et al.,* (2022) focused on the soil health endpoint of C sequestration (overlap with section 4.3) showing this was improved in Canadian wooded, compared to grass, riparian margins but similar in deciduous to coniferous stands. The authors also highted faster rates of C sequestration in restored woods than in old growth woods. The Brazilian study (Bieluczyk *et al.,* 2023) on approaches to riparian forest conversion from intensive landcover (sugarcane cultivation) has less relevance to temperate climates.

Primary studies on mycorrhizae covered riparian restoration by managed soil inoculation to aid tree establishment and soil services (Pagano *et al.,* 2022), or natural fungal transitions. Waymouth *et al.,* (2022) found that pasture to forest buffer conversion variously influenced mycorrhizae, with no clear effect, despite strong inter-site controls. Global review papers addressed questions of mycorrhizal role in nutrient retention during restoration management by riparian wooded

**Table 9. (a) Key aligned policies and strategies and (b) the three detailed gap statements concerning soil health as taken from the 2022 review and the number of new additional papers covering gap specifics reviewed here.**

| Sustaining soils | (a) Key policies and strategies | | |
|---|---|---|---|
| | • Scottish Soil Framework<br>• Scottish Biodiversity Strategy (SBS)<br>• Forestry Grant Scheme (FGS)<br>• Woodland Carbon Code (WCC) | • Scottish Rural Development Programme (SRDP)<br>• Agricultural Reform Routemap (2024)<br>• National Planning Framework 4 (NPF4) | |
| | **(b) Reviewed evidence topics** | **Detailed descriptions of specific gaps** | **n, papers** |
| | Improving soil health | Further research on quantifying the soil health benefits of river woodlands is required in the UK and Scotland, particularly with respect to soil biodiversity, physical properties and erosion resilience and enhancement of organic matter content and carbon storage. | 4 |
| | | Further research is required to understand river woodland mycorrhizae associations and their role in delivering multi-benefits including soil biodiversity, soil carbon storage and diffuse pollution control. | 5 |
| | Soil loss impacts | Further observation and modelling work is required to understand productive agricultural land loss and soil loss due to the lack of stabilising trees in the riparian zone and the economic implications. Economic analysis would include soil degradation and impacts on water quality, including the costs for remediating degraded soils and water (e.g. increased costs of removal of sediment during processing for drinking water supply). | 5 |

buffers. Correnblit *et al.,* (2018), focussing on planted willow margins for hydromorphic channel management, recommend ongoing knowledge needs on mycorrhizal functions in RW. Rubin and Görres (2021) showed how mycorrhizae enhance tree phosphorus uptake but that key questions remain (e.g. plant succession towards multifunctional mature RW).

Soil loss protection studies evaluated overlapped with the topic of bank erosion protection (section 3.1.1); here we sought papers that summarised the costs and effectiveness of RW. The primary data (n=3) and synthesis (n=2) studies were from New Zealand (pasture), US and France/Switzerland (mixed farming). Most publications used high numbers of study locations, thereby maximising evidence across site conditions. Fernandez *et al.,* (2017), using a biophysical-economic model for New Zealand, found riparian planting most cost-effective for bank erosion, but other mitigation and erosion controls (grass buffers, swales, stock reduction, fencing) better for field slope erosion. Zaimes *et al.,* (2019; 2021) showed that riparian trees, even in a thin band against farmland were effective against soil loss, and both bank and field slope erosion (more so than grass buffers). Philips (2024; New Zealand) and Tisserant *et al.,* (2020; France, Switzerland) examined RW relative to more managed techniques (rip-rap, gabions, geotextiles) where Philips (2024) had a context of traditional Maori cultural acceptance to measures and Tisserant *et al.,* (2020) a European context; both concluded that natural techniques were better than engineered approaches in most situations, or where necessary combinations. The studies had appropriate robust designs (e.g. high replication and multi-year durations) so were strong evidence for positive benefits but were limited to planted managed buffers only; evidence remains lacking for other woodland types.

### 3.7.2 Stakeholder engagement

Gap 18 on *RW effect on soil health and structure* was one of the top gaps through the prioritisation process in the workshop and also ranked high in the survey. Gap 19 on *RW effect on soil loss*, ranked slightly lower in both research phases but remained a high priority through the study.

Stakeholders acknowledged the interconnected roles of soil health, biodiversity, nutrient cycling, and carbon sequestration in RW areas but highlighted gaps in understanding RW specific effects, particularly in restoration sites. Calls for evidence on the "right tree in the right place" were frequent, with a focus on soil type, slope, and species selection to optimise benefits like soil stabilisation, sediment reduction, and fertility improvement. There was strong interest in aligning scientific knowledge with practical applications, such as flood mitigation and drought resilience.

While some stakeholders believed landowners would be interested in the economic impacts of soil loss, others felt this was already well understood. Interestingly, farming sector representatives did not raise soil health as a major concern during open-ended discussions, despite high rankings of soil-related evidence gaps in workshops and surveys.

#### Specific sectors interests and needs for further evidence

**Land managers and farmers:** Stakeholders in the farming sector underlined the need of data on economic gains from improved soil health, including reduced flood risks, better drought resilience, and overall farmland productivity rather than the need of soil specific information. They also mentioned a need for evidence on specific tree species' ability to thrive in various soil conditions, underlining a focus on sustaining soil health to support food production while mitigating erosion and pollution.

**Research and conservation:** There was an emphasis on the need for multidisciplinary studies addressing soil health, biodiversity, carbon storage, and their interactions at restoration sites. Mycorrhizae functions and interactions were mentioned once by an expert stakeholder.

**Policy:** Policy stakeholders emphasised the need for robust, accessible data on the economic and ecological impacts of RW on soil health, particularly in relation to agricultural resilience, flood mitigation, and animal welfare. The role of riparian tree planting in reducing soil loss, enhancing water infiltration, and improving overall land productivity was acknowledged. However, clearer guidance is required on best practices for tree species selection, planting density, and management to balance soil conservation and farm productivity. This could be addressed using mapping tools to determine optimal woodland placement for soil protection and water management. Calls for a more holistic understanding of the relationships between RW and the interconnected roles of soil health by policy makers are aligned with the main themes highlighted by wider stakeholders during survey and workshop engagement phases. Further specific needs indicated by policy stakeholders can be found in Appendix 3.

The needs highlighted by stakeholders are aligned with the objectives of the SBS to 2045. The SBS delivery plan (2025-2030) sets the objectives of developing a routemap for soil security in Scotland, reviewing and updating the Scottish Soil Framework, developing evidence-based Soil Health Indicators for inclusion in Whole Farm Plans as part of Rural Payments and Services agricultural support and Forest Management Plans. This aims to improve information for land managers on the assessment and interpretation of soil erosion risks, and the implementation of measures to avoid erosion particularly under extreme rainfall and drought events on soils. Addressing these objectives would support addressing evidence gaps related to soil health improvements and soil loss impacts.

### 3.7.3 Synthesis between stakeholder evidence perceptions, needs and current state of research on soil health

Holistic approaches for understanding the relationships between RW and multiple, interconnected soil heath indicators (nutrient cycling, carbon, agricultural productivity, flood and drought mitigation and biodiversity) were recommended by stakeholders and were noted as a key gap in both the survey and workshop. This likely stems from immature strategies for soil monitoring in Scotland and low levels of data collation, which was apparent in our evidence review and highlighted in the recent Risk to Scotland's Soils scoping report by Environmental Standards Scotland. The SBS objective for the development of evidence-based soil health indicators, and the requirement for land managers to conduct soil analysis to receive basic payment scheme payment under the Whole Farm Plan, could address the need for improved monitoring in Scotland. Monitoring soil health indicators across RW and non-wooded environments would be beneficial for understanding soil health improvement while also addressing wider evidence gaps.

Review papers addressing soil health indicators across chemical, physical/structural, nutrient cycling, microbial and C storage functions, should guide monitoring and future research and broadly matched stakeholder recognised benefits associated with 'healthy soils'. There was divergence of views on the importance of further research in enabling advances of soil health practice. The specific role of mycorrhiza in the restoration of riparian functions was found to require new mechanistic knowledge but had limited mention by stakeholders, although this could show a lack of understanding of importance outside of academia.

The development of maps to inform 'right tree, in the right place' for RW development was consistently highlighted by stakeholders. Additional spatial analysis of the Riparian Woodland Map of Scotland (NatureScot, 2025) could be conducted to understand stakeholder knowledge gaps related to which soil types, slope and wider environmental conditions are optimal for riparian woodland establishment to inform future planting. Further mapping of RW types other than riparian types is required. This supports a conclusion of the 2022 review (p12) to integrate best knowledge on existing riparian vegetation within river morphological classifications (for example within the SEPA MimAS framework). Previous recommendations for improved monitoring of soil health indicators will also support optimal woodland placement.

Recent Scottish-based research on the costs of soil erosion has not been specific to the role of woodland mechanistically (right tree, right place and bank erosion vs field slope erosion). Research combining soil loss and economic aspects (e.g. cost-effectiveness) with a specific riparian setting was dominated by US and Australasia studies. Although global knowledge is strong, research specific to UK costs and erosion conditions is required. Land managers and farmers were expected to be the beneficiaries of more mature research and guidance.

## 3.8 River corridor biodiversity and ecosystems

### 3.8.1 Current state of evidence

The specific gaps reviewed appear in Table 10 and the original evidence strength in Table 1. Many evidence gaps from the 2022 review were related to the influence of RW (particularly native woodland) on biodiversity and ecosystems.

The 2022 review notes there is very strong international evidence that RW support aquatic processes through regulating physical, chemical and biological conditions beneficial to freshwater biodiversity. However, gaps remained in the quantification of riverscape-scale nutrient recycling. We found no further evidence regarding the role of RW on nutrient recycling through ecosystems and trophic levels.

The strong evidence classification given in the 2022 review for the role RW play in supporting various species related to native RW supporting functions relating to terrestrial species including ones of conservation concern (including the benefits of including RW in agricultural buffer zones). The specific related gap statement addresses evidence limitations in relation to the interactions between large herbivores with RW. We identified a wealth of literature on the interactions between large herbivores and RW, specifically in Scotland, and particularly for deer and for beavers. Wilson *et al.,* (2023) reported that 11 years after the release of beavers in Knapdale Forest, Scotland, although 24% of stems in study plots had either been fully felled, partially felled or gnawed by beavers, 80% of these survived. Beaver-deer interactions were also investigated, with deer grazing on resprouted beaver-felled trees likely to suppress tree growth. Similar interactions were observed by Stringer *et al.*, (2015) in their review of beaver re-introduction in Scotland, who reported that 10 out of 11 studies reviewed recorded positive or neutral effects of reintroduction on the biodiversity of plants, including macrophytes, and herbaceous plants and trees. Negative effects include the role beavers play in creating ponds which can lead to the flooding of surrounding areas, increasing water retention and raising water tables. Flooding caused by dams can kill trees and later riparian zones not adapted to wet conditions.

Strong evidence for the role of RW in regulating local climates via shading was concluded in the 2022 review. Gaps remained in understanding the cooling, warming and insulating effects under different riparian canopies with or without the influence of groundwater discharge/resurgence, the extent to which temperatures in larger rivers can be managed through riparian tree planting in smaller rivers through effects on advected heat, and whether RW have an overall net benefit to fish populations in Scotland over other land-use types. No further evidence was identified in our review in relation to cooling warming and insulating effects, or the net benefits to fish populations. Dugdale *et al.,* (2024) found that optimal reductions in stream temperatures from riparian planting occur upstream channels with reduced channel width and lower water volumes, however, the authors note their study only considers temperature reductions in a single channel and doesn't examine the role of tree planting on advection in moderating stream temp in larger downstream rivers.

The 2022 review concluded there was moderate evidence related to habitat connectivity and diversity associated with research on native woodland regeneration and habitat connectivity in Scotland, RW targeting to improve species expansion and international evidence on connectivity benefitting genetic diversity through landscape-scale presence and restoration. Although there was no specific additional studies for Scotland, Bennett *et al.,* (2014)

<table>
<tr><th colspan="4">Table 10. (a) Key aligned policies and strategies and (b) the eleven detailed gap statements concerning river biodiversity and ecosystems as taken from the 2022 review, plus the four additional stakeholder defined gaps, with the number of new additional papers covering gap specifics reviewed here.</th></tr>
<tr><td rowspan="18">River corridor biodiversity and ecosystems</td><td colspan="3">(a) Key policies and strategies</td></tr>
<tr><td colspan="2">• Scottish Biodiversity Strategy (SBS)<br>• Scotland's Wild Salmon Strategy</td><td>• Scotland's Beaver Strategy</td></tr>
<tr><td>(b) Reviewed evidence topics</td><td>Detailed descriptions of specific gaps</td><td>n, papers</td></tr>
<tr><td>Aquatic processes</td><td>Research to further understanding riverscape-scale nutrient recycling and to quantify the benefits that river and riparian species play within this.</td><td>3</td></tr>
<tr><td>Supporting species</td><td>Further work on the impact and land required to accommodate rewilding. This includes understanding the interactions of large herbivores on river woods, their impact on riparian woodlands including ecosystem consequences and benefits.</td><td>4</td></tr>
<tr><td rowspan="3">Habitat connectivity and genetic diversity</td><td>Further field-based evidence with controls is required to quantify the effect of native woodland expansion on biodiversity, including river woodland networks.</td><td>3</td></tr>
<tr><td>Better understanding of genetic diversity of foundation river wood species in Scotland, and the implications for sourcing trees for re-establishment of river woods, supporting tree nurseries with native riparian species.</td><td>2</td></tr>
<tr><td>There is a need to identify a suitable focal species model for river wood habitat bird or bat/FWPM or aquatic invertebrate/lichen.</td><td>1</td></tr>
<tr><td rowspan="3">Regulating climate by shading</td><td>Further research is required to understand cooling, warming and insulating effects under different riparian canopies with or without the influence of groundwater discharge/resurgence.</td><td>0</td></tr>
<tr><td>Further research is required to ascertain the extent to which temperatures in larger rivers can be managed through riparian tree planting in smaller rivers through effects on advected heat.</td><td>2</td></tr>
<tr><td>Few studies have sufficient data to identify whether river woodlands have an overall net benefit to fish populations in Scotland over other land-use types.</td><td>0</td></tr>
<tr><td>Providing food for fish</td><td>Further research is required to quantify the importance of terrestrial invertebrates from river woodlands for the diet of fish in Scotland and subsequent impact on salmonid productivity with a comparison between different land-use types. (Further field work in Scotland with gut analysis on more streams and across Scotland will be beneficial to strengthen the evidence that semi-natural riparian woodlands compared to more intensively managed land-use types will improve invertebrate abundance food sources for salmonids) In a related area, further work is required to understand the complex interactions between food availability, competition (within, between fish species) and growth.</td><td>2</td></tr>
<tr><td rowspan="2">Improving fish habitat with woody material</td><td>Further research is required to understand the effects of large woody material on habitat and production of different native fish species. It will be important to understand how modifying habitat during restoration involving large woody material influences interactions and impacts on fish distributions and abundances.</td><td>1</td></tr>
<tr><td>Developing good predictive models which will help describe the complexity of changing interactions between Atlantic salmon, brown trout, and the animals that depend on them for food or for some other function, presents significant challenges. The development of such models will be helpful in understanding the ecological impact of changes in hydraulic habitat and habitat quality.</td><td>0</td></tr>
<tr><td rowspan="4">Biodiversity and ecosystems (stakeholder additions)</td><td>The interactions between invasive non-native species and river woodlands</td><td>2</td></tr>
<tr><td>The effects of habitat fragmentation on river woodlands</td><td>0</td></tr>
<tr><td>The effect of plant pathogens (e.g. phytophtera) on the expansion of river woodlands</td><td>2</td></tr>
<tr><td>The understanding of how ecological functions of river woodland interact spatially with human factors</td><td>0</td></tr>
</table>

studied the richness of bird species between sites with riparian and non-riparian vegetation across 24 landscapes in the agricultural region in Southeast Australia finding species richness decreased with tree cover loss. The 2022 review indicated the need to understand the genetic diversity of RW species in Scotland and the implications for sourcing native species and supporting tree nurseries. No further evidence regarding genetic diversity was identified, however, the Woodland Trust (2024) provided the example of the Loch Arkaig Pin Forest in Lochaber which is being supported by a community-owned tree nursery and makes recommendations for other nurseries. Further, NatureScot (2024) indicate there are now 20 gene conservation units for native Scottish tree species.

Evidence for RW supporting river hydromorphology and interactions with biodiversity was considered very strong in the 2022 review with respect to importance of native and floodplain RW and associated large wood material on hydromorphological and biological processes generally. Direct observational evidence at UK level was considered strong in relation to controlled studies and monitoring. Further mapping of RW types (structure and composition, biogeographical studies, reference condition) other than riparian types is required. This supports a conclusion of the 2022 review (p12) to integrate best knowledge on existing riparian vegetation within river morphological classifications (for example within the SEPA MimAS framework). This need is noted in later discussion of stakeholder comments.

For the specific RW benefit for wild fish and angling, the 2022 review determined there was moderate evidence for providing fish with food and weak evidence for improving fish habitat with woody material. The role of RW in providing invertebrate fish diets was examined by Kotalik *et al.,* (2023) in the Upper Arkansas River, USA, before and after restoration of riparian zones to include woody plants. Analysis of interactions between brown trout and invertebrate prey resources indicated that the trout population increased after restoration, however, reductions in aquatic insects and terrestrial invertebrates were also evident. The authors suggest increased trout population may have had a rebound effect on invertebrate populations. Similar increasing trends in trout populations were examined by Kratzer *et al.,* (2018) with the addition of large woody material in the East Branch Nulhegan River, USA. There was no further diet evidence for wider aquatic species, or the addition of woody material on fish habitats, specifically in Scotland.

Potential detrimental influences on RW and their long-term sustainability were identified by stakeholders, including the interactions between RW and non-native invasive species. Pattison *et al.,* (2019) conducted vegetation surveys of 20 lowland rivers in Central Scotland to determine factors that influence the abundance of native riparian vegetation and invasive Himalayan Balsam. Findings suggest Himalayan Balsam was sensitive to soil moisture and that riparian design should be managed to promote native vegetation to dominate. Gonzalez del Tanago *et al.,* (2021) call for better characterisation of riparian vegetation and the inclusion of indicators that monitor the number and coverage of alien/invasive species. Approaches to collect such information, including phytosociological sampling, remote sensing and fieldwork exist.

The threat of plant pathogens, such as phytophthora, on the expansion of RW, was also highlighted by stakeholders. There were no studies in Scotland addressing this gap, however, Corcobado *et al.,* (2023) found that 36% of 824 alder trees assessed in Austria were showing a decline due to phytophthora and 11.6% were dead, suggesting a potentially important issue for RW in Scotland.

Stakeholders indicated evidence gaps relating to the interactions between humans and RW and the impacts on ecological functions. Much of the literature on human interactions with RW is dominated by the negative impacts of land use change leading to the decline and fragmentation of RW coverage. Positive interactions are mainly covered in section 3.7.

### 3.8.2 Stakeholder engagement

Stakeholders widely recognised RW as critical for biodiversity, aquatic habitat health with strong interest in evidence supporting their role as ecological corridors. Gap 20 on *RW effect on overall biodiversity* was ranked highly due to its broad scope, while fish population gaps were also considered important topics, though experts noted a large amount of existing research in the survey and workshop. Other gaps ranked high through the study (*23 RW interactions with large herbivores; 25 Type of RW and river morphological outcomes; 21 Genetic diversity of native trees ; 24 Effects of RW for specific key species ; 44 Interactions between invasive non-native species and RW; 45 Habitat fragmentation and increases to RW connectivity),* some ranked medium *(31 RW and food sources for salmonids; 32 The cooling, warming and insulating* *effect of RW for fish ; 22 Characterisation of native RW structures and species composition),* and some low *(26 The effect of RW nutrient recycling through ecosystems and trophic levels ; 47 Ecological functions of RW spatial interaction with human factors*).

RW role in achieving good ecological status under the Water Framework Directive and biodiversity strategies was highlighted, alongside calls for long-term monitoring to understand benefits and trade-offs. Major barriers include grazing pressure from deer and sheep, concerns over beaver impacts, and high fencing costs. Stakeholders called for more research on herbivore management, fish-RW interactions, invertebrates, waders, and the resilience of tree species to invasive non-native species (INNS) and climate change.

While many stakeholders sought more evidence, some questioned whether certain gaps such as grazing interactions were more about implementation than research needs. A key tension exists between the urgency of addressing biodiversity loss and the time needed for rigorous studies, with some advocating better use of existing data over new research. Concerns were raised about RW unintended consequences, such as shading effects on aquatic food webs, and a perceived overly positive restoration narrative. Beavers were seen both as a challenge (due to tree damage) and a potential ally in habitat complexity.

### Specific sectors interests and needs for further evidence

**Forestry:** Evidence is required on the trade-offs between productive forestry and ecological benefits of RW; the development of guidance for tree species selection and planting strategies in sensitive habitats; approaches to balance natural regeneration and active planting.

**Agriculture:** Evidence is required on practical solutions for managing beaver and deer impacts on riparian zones; primarily concerned about financial risks, and compensation mechanisms in case of losses. This is also relevant for other sectors such as tourism.

**Fisheries sector and environmental management organisations:** Understanding the role of large woody material in improving fish habitats and potential negative effects; evidence on the effects of shading and habitat modification on fish species, particularly salmon, as well as trout; how to optimise riparian tree planting to mitigate river temperature increases.

**Conservation and restoration practitioners:** Holistic approaches to landscape management, particularly for herbivore control; research on the biodiversity benefits of RW, including habitat connectivity and species-specific impacts; better understanding of the impact (and opportunities) of invasive species on RW; and understanding the roles and potential effect of trees in designated areas such as peatland.

**Private sector:** Highlighted a need for improved monitoring for better evidence on biodiversity benefits, specifically for biodiversity credits. Demonstration sites and showcase materials were identified as critical to illustrating benefits and securing organisational buy-in.

**Policy:** Policy stakeholders (Appendix 3) highlighted evidence gaps related to conflicts and synergies with a broad range of policy relevant topic such as habitat connectivity, herbivore management, biodiversity net gain, invasive species control, and biosecurity risks as wider biodiversity priorities.

*Biodiversity policies:* The SBS states that by 2044 “Nature Networks across our landscapes will underpin the resilience and health of species and habitats.” In the context of delivering this more integrated, ecosystem-based approach to biodiversity policy, concerns were raised about ensuring that woodland creation strategies enable multiple conservation goals to be achieved e.g., how much tree cover sensitive habitats like wetlands and moorlands can sustain without ecological trade-offs. Improved understanding of hydrology and habitat functionality was seen as critical to informing decisions on woodland creation, particularly in areas where current restrictions (e.g. land management) may no longer align with evolving policies on RW. This is linked to the SBS Delivery Plan Actions 19.4 ‘Increase biodiversity across all woodlands by increasing the characteristics that improve woodland condition’ and Action 19.5 ‘Identify where woodland can have the most benefit for water resource management using an evidence-based approach and implement through a range of mechanisms including forestry grants and private restoration initiatives.’

*Deer management policy:* Effective deer management is fundamental to enabling woodland creation, with calls for more research into effective and ecologically sustainable management strategies beyond heavy reliance on deer fencing. Participants emphasised the need for a landscape-scale approach that integrates herbivore management with broader land-use priorities, including livestock impacts on RW. This objective is part of the SBS Delivery Plan “Action 5.3 Explore how best to support optimal herbivore densities to enhance biodiversity outcomes in the uplands. Scottish Government NatureScot ongoing; Action 5.4 Review the use of mechanisms to support effective and safe deer management in new and existing woodlands and neighbouring open habitats.".

*Beaver policy:* The Scottish Government has changed its policy to encourage beaver restoration as a 'key ecological component of restored rivers and wetlands by 2045' (SBS). Stakeholders discussed techniques for managing and mitigating the impacts of beavers in the context of the SBS objective to 'maximise the environmental and wider benefits of beavers …' and highlighted the need for ongoing research and monitoring of the beaver population and its effects.

*Invasive non-native species policy:* Managing INNS within RW (e.g. Japanese knotweed, grey squirrels) as land transitions to less-grazed habitats was a key stakeholder concern. This is highlighted in the UK Forestry Standards: 'riparian woodland … can also facilitate the rapid spread of invasive species such as Japanese knotweed and giant hogweed, ... Water can often act as a pathway for spreading invasive non-native species.' Additionally, biosecurity risks associated with RW, particularly in relation to INNS spread and impacts on water quality and aquatic species, requires more investigation. Some participants questioned whether certain non-native species could offer ecological benefits in a changing climate, and this could be an area for research. The SBS Delivery Plan (2024-2030) includes actions to 'Develop and implement the Scottish Plan for Invasive Non-Native Species (INNS) Surveillance, Prevention and Control to enable long-term effective INNS removal at scale' and it would be prudent to ensure this takes account of the risks associated with expanding catchment woodlands.

*Wild Atlantic salmon policy:* The Conservation of Salmon (Scotland) Regulations 2016 introduced legislation to protect declining wild Atlantic salmon stocks, and the many resulting actions for Atlantic Salmon (which include extensive wood creation) are widely recognised as having significant and wide-ranging benefits for Scottish biodiversity.

*Biodiversity net gain:* There was interest in understanding whether RW could compensate for the loss of native trees due to development, aligning with biodiversity net-gain policies.

### 3.8.3 Synthesis between stakeholder evidence perceptions, needs and current state of research on river corridor biodiversity

The evidence for biodiversity loss in Scotland is indisputable, prompting government commitments in the SBS to halt and reverse these declines. Given this urgency, stakeholders have identified nature recovery as a priority, with a strong interest in both species-specific and ecosystem-level effects of RW. However, much of the existing evidence comes from outside the UK, while studies conducted in Scotland, primarily on benthic macroinvertebrates and fish, have produced limited findings. Ongoing projects aim to strengthen this knowledge base and address what some perceive as an "overly positive narrative" about RW benefits. Research on the impacts of invasive species, browsing pressures, and beaver activity is well-established, shifting the focus toward effective management strategies, such as protection measures, planting techniques, and species selection. Additionally, understanding the genetic diversity of RW species and the implications for sourcing native stock remains a critical gap.

A particularly active area of research is the role of instream large wood structures (LWS), especially in Scotland's dynamic highland rivers (Soulsby *et al.,* 2024). While LWS are widely used in smaller watercourses, their design and effectiveness for habitat improvement in larger, high-energy rivers remain uncertain. Existing evidence on their hydromorphological and biodiversity benefits at multiple scales is sparse, and further dedicated research is needed. A new three-year collaboration led by Exeter University, in partnership with Edinburgh University and SEPA, will begin in late 2025 to investigate these effects in both Scotland and England. Meanwhile, LWS placements continue to be implemented, with growing observational support for their ecological benefits.

In the face of the biodiversity crisis, the role of native RW in supporting species recovery is widely assumed but lacks robust UK-specific evidence. Key research priorities include understanding ecosystem as well as species-level benefits and trade-offs, identifying solutions to barriers and future threats, and, assessing the reach-scale effects of LWS. This also implies determining the timescales over which RW benefits such as bank stabilisation, canopy shading, and large wood inputs will become fully realised and evolve over time.

## 3.9 Health, wellbeing, cultural heritage and community involvement

This section addresses the scientific evidence against five gaps for human health and wellbeing identified by the 2022 review and a further three gaps identified by stakeholders relating to cultural heritage and community involvement.

### 3.9.1 Current state of evidence

The specific gaps reviewed appear in Table 11 and the original evidence strength in Table 1. The benefits of exposure to RW for human health was determined as having strong evidence in the 2022 review based on strong knowledge on the biophysical processes, quantified evidence on positive health effects from woodland exposure (and whilst this didn't relate directly to RW, it was presumed transferable). A greater evidence-base on mental and physical health outcomes of RW within the European context and the economic benefits for the National Health Service (NHS) were identified as gaps in the 2022 review. Although our review didn't identify specific health and physical benefits related to RW, the review did identify the positive influence of the exposure of blue spaces in Scotland on health and well-being based on 1,392 national survey respondents (McDougall *et al.,* 2022). Further, Alejandre *et al.,* (2023), in their literature review of blue prescription programmes, found that service users across sixteen studies reviewed, including both qualitative and quantitative studies, demonstrated improvements in physical, cognitive and social health. The Scottish-specific study reporting that blue spaces lead to positive health and well-being outcomes strengthens the evidence gap.

**Table 11. (a) Key aligned policies and strategies and (b) the five detailed gap statements concerning soil health as taken from the 2022 review, plus the three additional stakeholder defined gaps, with the number of new additional papers covering gap specifics reviewed here.**

<table>
<tr><td rowspan="11">Health, wellbeing, heritage and communities</td><td colspan="3">(a) Key policies and strategies</td></tr>
<tr><td colspan="2">• National Planning Framework 4 (NPF4)<br>• Improving access to greenspace (PHE, 2020)<br>• Mental health and wellbeing strategy: outcomes framework, Scottish Government</td><td>• Scottish Government, Improving access to green spaces<br>• Scotland's Our Natural Health Service (ONHS)<br>• Green Health Partnerships (GHP)</td></tr>
<tr><td>(b) Reviewed evidence topics</td><td>Detailed descriptions of specific gaps</td><td>n, papers</td></tr>
<tr><td rowspan="2">Exposure to river woodland</td><td>Many studies on psychological effects of nature exposure have been carried in SE Asia, with some results limited by experimental design. More research in Europe is required, with studies with larger sample sizes and in river woodlands.</td><td>4</td></tr>
<tr><td>Further work is needed to quantify the impact and potential savings for the NHS, including the use of river woodland areas as part of green prescriptions providing more structured healthcare.</td><td>2</td></tr>
<tr><td rowspan="3">Cooling air</td><td>Very little empirical evidence has been collected on the relative importance of different tree characteristics for their cooling capacity in the temperate region. The impact that the radiative properties of different tree species may have on urban thermal conditions in temperate climates has been less studied.</td><td>3</td></tr>
<tr><td>Further research is required to understand how best to design urban blue-green infrastructure involving river woodland types to optimise cooling for health benefits.</td><td>2</td></tr>
<tr><td>Further research is needed to understand the impact of wooded riparian zones in Scottish cities on the urban heat island effect and health benefits.</td><td>4</td></tr>
<tr><td rowspan="3">Social, cultural and heritage (stakeholder additional topics)</td><td>The relationship (synergies and impacts) of restoration projects on local cultural heritage and archaeological sites.</td><td>0</td></tr>
<tr><td>The understanding of community preferences, social and political perceptions of river woodland restoration.</td><td>0</td></tr>
<tr><td>How mechanisms for developing restoration projects are socially acceptable, just and beneficial to local communities.</td><td>0</td></tr>
</table>

Monetary savings from interactions with blue spaces and RW specifically haven't been quantified for the NHS. Quantifications for green space interactions are available, with The Wildlife Trust (2023) reporting savings of £200,100 across five programmes. Drayson *et al.,* (2014) estimated that equitable access to green space could save the NHS approximately £2.1 billion per year by reducing treatments for cardiovascular diseases, stroke, and type 2 diabetes. Further, the report mentions that visiting woodlands can have significant positive impacts on mental and physical health, particularly for those living with dementia.

Strong evidence of the cooling benefits of RW was concluded in the 2022 review, including for the magnitude of cooling effect increasing with the size of blue- and green- space. Specific gaps remained in relation to the cooling capacities and characteristics of different tree species, how to best design blue-green infrastructure in the urban context to optimise cooling and the impacts of wooded riparian zones in Scottish cities on the urban heat island effects. Emmanuel & Loconsole (2015) found a 20% increase in green cover over the present level in the Glasgow Clyde Valley region would be required to reduce surface temperature by up to 2°C. Tsia *et al.,* (2017) conducted hourly monitoring at 20 paired locations (riparian and non-riparian) for two years in Sheffield, UK. Riparian corridors were generally 1°C cooler than non-riparian locations in summer and could be up to 3°C cooler in extreme hot weather. Both studies further strengthen the evidence for supporting good health and the cooling effects of RW. We found limited evidence relating to the cooling capacity of specific tree species. Scholz *et al.,* (2018) used the i-tree model to generate estimates of trees species that had the greatest surface temperature reduction in Duisburg, Germany. The i-tree model could be applied to investigate surface temperature reductions of species in the Scottish context.

Stakeholders identified additional evidence gaps related to the interactions between RW restoration and cultural heritage, and both the need for a better understanding of community preferences regarding RW, and mechanisms to ensure restoration projects are socially acceptable. We identified no evidence for any of these gaps, the majority of literature is dominated by general co-production processes for nature restoration or water management, which could be applied in the RW context.

### 3.9.2 Stakeholder engagement

In the first two stages of engagement the human health gaps (*27 Mental and physical health outcomes of RW; 28 RW integration to urban settings; 29 The economic effects of RW on the NHS; 30 RW effect on dissolved organic carbon in drinking water*) were ranked fairly low in priority, similarly to the archaeology gap (*40 The effect of restoration projects on local cultural heritage and archaeological sites*). Potentially this is because stakeholders involved mostly had backgrounds in ecology and related topics, although insights from some domain experts gave us some priority perspectives within their field. Nevertheless, there is a broad consensus among all stakeholder groups that RW contribute positively to both physical health and mental well-being. Topics of social acceptability were added to the list following the survey and noted as high importance by stakeholders across all expertise (*41 Community preferences and perceptions of RW restoration; 42 RW socially acceptable, just and beneficial to local communities*). Gap 30 on *RW effect on dissolved organic carbon in drinking water* also linking to the topic of water quality was upgraded in priority after the open-ended phases of engagement.

### Specific sectors interests and needs for further evidence

**Public health:** The health sector sees RW as valuable for well-being but lacks Scotland-specific data to inform policies. Funding gaps limit the scalability of nature-based interventions, and socio-demographic inequalities restrict access to green spaces. There is a need for better data on how access to RW influences pro-environmental behaviours, as well as more inclusive program designs to ensure equitable benefits. There is a need for evaluation frameworks measuring the holistic benefits of nature-based solutions, including mental health improvements. Some stakeholders are concerned about the ecological impact of increased access to green spaces, calling for monitoring programs to balance health and environmental benefits.

**Cultural heritage and archaeology:** Cultural heritage and archaeology impacts remain underexplored, with a lack of metrics assessing RW social and immaterial benefits, such as well-being and community cohesion. Evidence is needed to understand the preservation of wetland archaeology during restoration, particularly the impact of tree planting and morphological changes. Cultural heritage also informs sustainable management.

**Agriculture and land management:** Farmers face barriers to adopting conservation measures, prompting calls for targeted incentives. There's also a need for aligning private finance initiatives with ecological goals to make conservation viable.

**Private finance:** Investors seek metrics to measure both material and immaterial benefits of RW restoration for communities, alongside ecological benefits and health improvements.

**Policy:** Access to greenspace is essential for improving public health and enhancing quality of life, yet barriers to visiting these spaces remain. A 2020 review on Improving access to greenspace (PHE, 2020) identified several well-documented barriers to accessing greenspace, but further research is needed to investigate the deeply held personal values and perceptions that influence both motivations and self-reported barriers. Understanding these factors will help to create more effective policies and programs to encourage increased engagement with nature. For individuals to engage with greenspace, they need to have the opportunity to access it, feel capable of using it, and see tangible benefits in their lives. Thoughtful and purposeful physical design, such as spaces that encourage more active use, can play a significant role in removing barriers to engagement. While general strategies to encourage greenspace use have been shown to be effective, there is still a need to understand the variation in outcomes across different demographic groups. Research into the factors that influence the effectiveness of these approaches for diverse populations is crucial to tailor interventions and maximise their impact.

The National Planning Framework 4 (NPF4) has highlighted the value of expanding greenspace, particularly through urban woodland creation, as an essential strategy for improving air quality, managing water, and cooling urban environments. Wider woodland expansion in urban areas can make a significant contribution to improving the quality of life by reducing pollution, supporting biodiversity, and increasing resilience to climate change. Furthermore, blue and green networks can help create more compact, liveable cities, aligning with broader urban greening goals. Waterfront regeneration offers additional opportunities to enhance urban resilience and environmental sustainability. Scotland's coasts, estuaries, and river corridors have strategic importance for climate mitigation and resilience. As climate change impacts coastal areas, it will be critical to manage coastal erosion, flood risks, and storm surges through natural solutions that work with the unique biodiversity and landscape character of these regions while creating additional societal benefits for health and recreation. Projects along the Inner Forth, for example, are providing multiple benefits, including habitat creation, flood management, cultural landscape enhancement, and improved access to waterfront spaces. By continuing to unlock the potential of these areas, their contribution to environmental change and improve access to nature for local communities can be further strengthened.

In parallel with these efforts, sustainable forest management remains a key priority. The UK Forestry Standard stresses the importance of protecting the historic environment in forest management planning. As more information is gathered through archaeological surveys and research, it is essential to involve heritage professionals in decisions on woodland regeneration that affect the conservation of cultural and historic sites. Identifying and safeguarding heritage features, particularly in areas slated for woodland creation, ensures that conservation efforts integrate the protection of cultural heritage with ecological goals.

Green Health Partnerships (GHP) (Mitchell and Finton, 2022) are the cornerstone of Scotland's Our Natural Health Service (ONHS) program that seeks to enhance public health by promoting the use of Scotland's natural environment. Led by NatureScot, alongside partners from national and local government and the voluntary sector, the programme aims to connect health and environment sectors to improve both physical and mental health outcomes, while addressing health inequalities. As a key implementation element of the ONHS programme, four pilot Green Health Partnerships were launched in 2018 to demonstrate how cross-sectoral collaboration can mainstream approaches to health improvement through engagement with the natural environment. These partnerships have shown how nature-based interventions can be integrated into health and social care strategies to tackle health disparities. GHPs have identified the need to engage politicians and healthcare professionals at both local and national levels as green health champions. In addition, GHPs have explored integrating green health referral pathways into social prescribing services, enabling healthcare professionals to recommend nature-based interventions as part of treatment plans. However, there are concerns about the short-term nature of GHP funding and the reliance on third-sector, community, and voluntary organisations for delivering interventions. Stakeholders have called for sustainable and appropriate funding models to ensure the long-term success and impact of green health initiatives.

#### 3.9.3 Synthesis between stakeholder evidence perceptions, needs and current state of research on health, wellbeing, cultural heritage and community involvement

There is a strong evidence base supporting the public health-related benefits of woodlands, alongside evidence highlighting the health and climate benefits of water bodies. However, there is a notable gap in research regarding how the combination of woodlands and rivers may interact to provide benefits beyond those that each delivers in isolation. While quantified economic benefits for green spaces have been documented, there is limited evidence on the specific impacts of RW, particularly their potential to reduce NHS costs. Health-sector stakeholders have specifically pointed out the need for more Scotland-specific evidence to support the integration of these nature-based solutions into public health strategies.

A significant concern raised during stakeholder engagement is the lack of evidence on community acceptability, which is critical to the success or failure of restoration efforts. The absence of studies on community preferences or social acceptability, particularly for RW was identified as a key gap in the existing research. This highlights the importance of understanding how communities perceive and accept restoration projects, as their support or resistance can directly influence the outcome of such efforts. Stakeholders also emphasised the importance of aligning restoration projects with community and cultural values, balancing ecological and social goals. Health-sector stakeholders noted that the lack of Scotland-specific evidence and the absence of monetised benefits for RW within the NHS framework hinder the integration of these nature-based solutions into public health strategies. Furthermore, the lack of scientific evidence on the social acceptability of RW presents a critical gap that could undermine restoration efforts.

Addressing these gaps requires a focus on community engagement, co-creation of restoration projects, and transparent communication. Public awareness campaigns and fostering trust through clear communication about the benefits and potential trade-offs are essential in overcoming resistance and ensuring the success of RW restoration efforts. By aligning ecological goals with social and cultural values, and addressing evidence gaps in acceptability, future restoration projects have the potential to be inclusive and effective in achieving both environmental and public health outcomes. River woodland restoration projects may, in the future, be considered for Green Health Partnerships under the Our Natural Health Service programme, provided that evidence gaps on their benefits and challenges to secure longer-term funding can be addressed.

## 3.10 Food and biomass production and utilisation

#### 3.10.1 Current state of evidence

The gaps reviewed appear in Table 12 and the original evidence strength in Table 1. Overall the 2022 review concluded there was strong evidence that woodlands provide shade and a cooling effect for livestock, including physiological studies on livestock (although not specific to RW). Gaps related to conflicts between the role of RW in providing shade for animal welfare and bank stabilisation goals were identified in the 2022 review. De Sousa *et al.,* (2018) found there was no difference in soil composition between riparian zones and surrounding land covers in the Conway Catchment, Wales. Sheep and cattle farming are the main land uses in the catchment, however, the practices are non-intensive. The paper does refer to literature beyond the review study period, including Stutter *et al.,* (2012) and Burger *et al.,* (2010) who describe differences in soil physiochemical properties between riparian zones and fields with intensive agricultural properties. The gap could conflict with Scottish environmental regulation, as livestock interaction with the riparian zone shouldn't be encouraged as per SEPA's General Binding Rules.

The 2022 review highlights there is overall moderate evidence to suggest RW can provide fodder for livestock, despite stronger evidence that tree leaves have nutritional and medicinal benefits for livestock. A further gap regarding the nutritional and medicinal benefits of tree fodder for livestock productivity in Scotland was identified in the 2022 review however, no further relevant evidence was identified.

Strong evidence that RW support pollination to sustain food production was noted in the 2022 review. This was associated with both the well-research topics of insect food and habitat along woodland edges and the additional benefits that pollinators bring to crop production when habitats are enhanced generally (not specific to RW). The need for a greater understanding of how to design

| Table 12. (a) Key aligned policies and strategies and (b) the five detailed gap statements concerning food and biomass as taken from the 2022 review and the number of new additional papers covering gap specifics reviewed here. | | | |
|---|---|---|---|
| **Food and biomass** | **(a) Key policies and strategies** | | |
| | • Forestry Grant Scheme (FGS)<br>• Woodland Carbon Code (WCC) | • Scotland's Forestry Strategy (SFS)<br>• Scottish Rural Development Programme (SRDP) | |
| | **(b) Reviewed evidence topics** | **Detailed descriptions of specific gaps** | **n, papers** |
| | Shade for livestock | Whilst the benefits of trees for shelter and shade for animals is well understood the specific role of riparian woodland is less well studied and there may be conflict between this role and bank stabilisation goals and animal welfare. The impact of livestock and stock density on different soil types and in different settings, both in uplands and lowland riparian zones in Scotland, requires further assessment. | 1 |
| | Providing fodder for livestock | The impact of the nutritional and medicinal benefits of tree fodder for livestock productivity requires further quantification in Scotland. | 0 |
| | Supporting pollination | The pollinator research covers woodland edge and designed buffer strips with and without woodland. It is not clear whether riparian zones would be in the right locations, and at sufficient density across the farm to provide the pollinator benefits identified in the measured effect from planted wildflower blocks. Further research is needed to understanding better the design of heterogenous landscapes to optimise crop pollination. | 1 |
| | Provision of biomass for energy | Further work in Scotland is required to understanding the benefits of short rotation coppice and its impact on water and soil quality. Also, to understand the economic benefits to farm enterprises in a Scottish context from biomass provided from riparian woodlands | 3 |
| | | Further evidence to support the use of Short Rotation Coppice and Short Rotation Woodland in purification/phytoremediation in final water treatment systems on farms, coupling wastewater management with renewable energy in Scotland. | 1 |

heterogeneous RW landscapes to promote crop pollination was identified in the 2022 review. Deepthi *et al.,* (2020) found that the conservation of riparian zones increased the pollination service to coffee plantations in South India. Bee colonies were used as indicators of pollinators, and their visitations to plants at distances of 10, 30 and 60m for the riparian zone were measured with greater distances resulting in fewer pollinator visitations. Despite not mentioning the specific riparian tree species, the research indicated that bee colonies were found in tree cavities and fallen logs. While South India's climate and coffee production are not relevant to Scotland, the methodology used could be replicated in Scotland.

The 2022 review concluded there was strong evidence that RW, specific to willow in man-made riparian buffer zones, could provide biomass for energy, including UK field-scale evidence and at farm scales in Danish and U.S. studies. However, the effects of short rotation coppice in RW on water quality and soil, and analysis of the economic benefits of the practice, were identified as gaps in the 2022 review. No evidence was identified for Scotland, however, Adams *et al.,* (2024) demonstrated that short rotation coppice willow reduced both particulate phosphorus and total phosphorus loads to watercourses at the micro catchment scale. Livingstone *et al.,* (2023) conducted an economic assessment of a hypothetical short rotation coppice system within the riparian zone of a typical Northern Irish farm over a 25-year period across three scenarios; 1) direct chip harvesting, 2) full-stem harvesting, and 3) a scenario with a guaranteed purchasing contract for fresh chip. The full-stem scenario returned the highest economic return of £497/ha/yr. In a full farm comparison, the removal of dairy land for the riparian buffer resulted in a reduction of £28/ha/yr. As part of the economic assessment, nutrient removal payments to farmers for the adoption of willow riparian buffers were investigated. The payment assumes the cost of £8.86 to remove 1 kg of N and P in a wastewater treatment plant, multiplied by the total N and P removed at each harvest, totalling £1660/ha per harvest returns.

### 3.10.2 Stakeholder engagement

Stakeholders highlighted the need for better understanding of RW integration in agricultural landscapes, balancing economic benefits (e.g., biomass markets, soil health) with costs (e.g., fencing, loss of productive land). Farmers were particularly concerned about losing productive land, while discussions on RW-livestock interactions were limited. There was no specific discussion of the interactions between RW and livestock management as worded in the project gaps 34 *Nutritional and medicinal effects of tree fodder for livestock* and 35 *RW and crop pollination*. However, further evidence was requested on the economic and practical implications of RW on farms, including its role in improving resilience and sustainability linking to the high importance of gap 33 *RW and livestock management and farming economics*. Scepticism exists around biomass markets, with concerns about economic feasibility, appropriate planting scales, and limited local incentives in Scotland. This is why gaps 36 *the effect of short rotation coppice RW on water and soil quality* and 37 on *the viability of biomass markets for RW* remained lower priority in the survey and workshop.

#### Specific sectors interests and needs for further evidence

**Agricultural sector and forestry practitioners:** Farmers are aware of existing evidence on the economic and practical implications of integrating RW on farmland but face barriers to implementation including time, energy, and financial constraints that limit implementation. Clear definitions of the respective benefits of different planting types (e.g., single trees, lines, groups) to farm systems were requested. Strategies to manage conflicts, such as fencing that may inadvertently restrict livestock access to water, were called for. Evidence is required to better understand how tree planting in the lowlands might align with food security objectives, with concerns that misplaced afforestation may reduce the availability of grazing and arable land. Related to this, improved guidance in relation to addressing pressures unique to integrating RW into arable landscapes was seen as highly important for lowland restoration efforts.

Reframing existing evidence to clarify the economic trade-offs for farmers and other land-managers would help to overcome barriers in relation to managing interactions between potential animal welfare benefits, riparian stability, and compliance with regulations around livestock interactions with RW (e.g., SEPA's General Binding Rules).

**Policy:** Greater clarity is needed from policymakers and agencies in relation to awarding grants funding for restoration, and the potential economic benefits for farmers, and including compensation mechanisms for land lost to tree planting. Development, trialling, and uptake of innovative and coherent funding mechanisms, perhaps involving use of biodiversity and carbon credits, may offer routes to achieve a balance between food production and conservation goals. This may also contribute to reducing financial risks for land managers and improve engagement with, and uptake of, climate and biodiversity initiatives incorporating RW. More specifically, addressing scale-related challenges related to current agri-environment and forestry grants would facilitate smaller-scale woodland creation. SNAP 3 Outcome One Nature Connects – Objective 3 2025, states that eligibility for SBS DP farming support payments will require farmers to establish the foundation of a "Whole Farm Plan." This plan must incorporate soil analysis, animal health and welfare strategies, carbon audits, biodiversity assessments, and integrated pest management practices.

Forest restoration policy might usefully be informed by landscape-scale analysis tools like LiDAR to identify optimal tree-planting sites capable of balancing environmental and agricultural benefits. There was also a call for data to be made available on the economic costs and benefits of riparian woodlands managed for biomass, including its potential to enhance soil health, mitigate flooding, and support animal welfare. This also needs to consider the longer-term cost and management implications for restored areas. More specifically, concerns were raised about the logistical and financial barriers associated with providing off-stream water access for livestock when riparian tree planting is implemented.

Policy related opportunities currently exist that may help to address some of these issues. The Scottish Government is currently working to establish a robust framework to underpin the future agricultural support regime, with the goal of delivering high-quality food production, climate mitigation, and nature restoration. This links to the development of the natural capital market framework to ensure that it complements private investment opportunities.

### 3.10.3 Synthesis and summary: stakeholder evidence perceptions, needs and current state of research on food and biomass

Evidence gaps relating to biomass and food production were generally considered lower priority than others in this project. Agricultural sector stakeholders' central concern was the economic feasibility and viability of adding trees to their farms with barriers such as upfront costs, time and competing policy goals continuing to hinder engagement. Reframing the evidence to emphasise the economic benefits would increase its utility for the agricultural sector.

Stakeholders engaged in this study, expressed scepticism about the benefits of short rotation coppice in relation to its economic feasibility and environmental impacts when used for biomass production. Disseminating recent evidence, as noted above, more widely and conducting further research to promote the economic and practical applicability of short rotation coppice could help engage the farming community especially where relevant to their needs. However, environmental concerns about its potential impacts on biodiversity and water systems, need to be addressed alongside any economic case. Recent evidence on the benefits for water quality will become more relevant as related practices are developed, and this is an important priority for stakeholders. Finally, they saw little immediate need for further evidence on the biodiversity related benefits of RW for crop pollination.

Additionally, improved guidance tailored to practical implementation and the development of innovative funding mechanisms, such as biodiversity credits and payments for ecosystem services would be of benefit. Innovative "hybrid" funding mechanisms could help bridge gaps between conservation and agricultural priorities. Finally, specific calls were made for clearer guidance on how to select appropriate planting regimes, and implementation of RW restoration in lowland settings. While policymakers and researchers emphasise RW role in broader policy strategies, farmers prioritise immediate benefits such as livestock shelter and overgrazing mitigation. Ownership complexities along riverbanks and fencing responsibilities further complicate woodland creation, highlighting the need for collaborative frameworks to support implementation.

# 4 Prioritisation of evidence needs and pathways

## 4.1 Stakeholders' identified challenges for river woodlands and main evidence needs

Overall engagement with a wide range of stakeholders revealed that a lack of evidence is not the primary challenge to RW restoration. Stakeholders varied in their familiarity with and ability to engage with scientific evidence. Discussions with stakeholders often intertwined insights on evidence, practical challenges, and lived experiences, highlighting the need to consider evidence needs within the broader context of RW challenges. The complexity of these discussions stems from the interconnectedness of formal evidence needs and overarching challenges, which may require interventions beyond research and development, such as policy changes and funding support. Notably, the challenges related to policy implementation, as identified by policy stakeholders (Appendix 3), closely aligned with the broader range of challenges raised by other stakeholder groups. These challenges are:

**Lack of funding, incentives, and resources**

Stakeholders identified financial constraints as a major barrier to RW restoration, particularly in securing adequate funding, staff, and skills. Stakeholders involved in the projects highlighted the importance to bridge the funding gap through blended finance solutions, linking public, private, and philanthropic investment. The Riverwoods Initiative highlights RW as a nature-based solution to climate change, advocating for integrated financial mechanisms such as biodiversity markets and carbon credits to support long-term investment. As this challenge remained major concern for stakeholders, we explored this further in our diversifying funding consultation Appendix 4 and consider it as part of our pathways in section 4.4.

**Grazing impacts**

Managing grazing pressures from deer and beavers was highlighted as a critical barrier to RW restoration. The SBS Delivery Plan explores how best to regulate herbivore densities to support woodland regeneration and reviews mechanisms for effective and safe deer management, acknowledging the need for strategic interventions in new and existing woodlands. The LINK Deer Group suggested stricter regulations in priority areas like RW. They also recommend encouraging deer population reduction instead of relying on fencing which could hinder large-scale ecological restoration. Anticipated reforms in the upcoming Natural Environment Bill (NEB) could represent opportunities to modernise deer management in Scotland. Scotland's Beaver Strategy highlights ecosystem benefits provided by beavers, such as water storage and biodiversity support, suggesting that financial support for RW restoration could align with beaver habitat expansion. Clearer policies and adaptive management strategies are required to balance grazing control with ecological benefits and work is currently being carried out to monitor the delivery of the Beaver Strategy to answers some of these challenges.

**Spatial complexities and landowner involvement**

There is a need for clearer policies, including defined areas for RW restoration and coverage targets. Cross-boundary challenges, such as shared ownership of riverbanks, further complicate RW restoration efforts. Stakeholders have called for clearer guidance on expanding RW that considers local specifics and challenges, ensuring alignment with the SBS afforestation and biodiversity goals, as well as the Scottish Government Climate Change Plans. Recent guidance on RW management has been provided in the 2024 UK Forestry Standard Practice Guide, Creating and Managing Riparian Woodland. Beyond guidance, encouraging landowner participation and fostering community support were recognised as essential for successful RW projects. Concerns about land use restrictions, financial risks, and maintenance responsibilities often deter participation. The SBS envisions RW as a key component of river system restoration by 2045. Additionally, the NPF4 and Nature Networks support woodland expansion by requiring Local Development Plans (LDPs) to identify and protect woodland areas while ensuring ecological connectivity. However, for this vision to be effectively realised, landowner incentives must be designed to align with spatial and local complexities, addressing the challenges of implementation.

**Climate change vulnerability and resilience**

Stakeholders emphasised the need for RW strategies to address and adapt to climate change risks, expressing concerns about their resilience in the face of changing conditions. River woodlands have the potential to play a key role in mitigating these risks, particularly in relation to drought, flooding, and biodiversity loss. The recently published Scottish National Adaptation Plan (SNAP3) outlines strategies and objectives for building climate resilience, presenting an opportunity to harness RW as nature-based solutions. Additionally, the SNAP3: Monitoring and Evaluation Framework details how progress toward these goals will be measured, including relevant monitoring strategies. This presents an opportunity for reciprocity and synergies. Improving evidence and implementation plans for monitoring RW could inform SNAP3's monitoring efforts, while SNAP3 could, in turn, support the implementation of these strategies.

**Collaboration and knowledge sharing**

Greater integration and cross-sector knowledge sharing, along with the development of shared evidence, are essential for advancing RW efforts. The need for collaboration extends beyond Scotland, as highlighted in Urbanic *et al.,* (2022) on RW policy, which recommends a policy co-creation approach and enhanced knowledge transfer. A gap exists between contemporary scientific knowledge and decision-making, making the policy-science interface co-creation model crucial. This model facilitates knowledge exchange and co-creation, ultimately enriching decision-making processes. By fostering collaborative policy development, we can enhance riparian zone sustainability, leading to resilient ecosystems and improved human well-being. Initiatives such as Riverwoods and the development of its strategic blueprint demonstrate progress toward these goals in Scotland.

Characterising the evidence needs that limit implementation of RW should be considered in the context of this wider range of challenges that emerged consistently across all phases of engagement. Research and development priorities should focus on addressing evidence gaps that may help overcome these challenges. The project highlighted overarching evidence needs priorities for advancing practice. Gaps in the areas of flooding, drought, water quality and biodiversity were predominantly a priority across the whole range of stakeholders, although in general more part of a call for integration of evidence and adapted tools across benefit areas than a focus on single area evidence needs. Inter topic priorities that emerged across all topics and stakeholder engagement are:

- Evidence for optimising tree placement: Developing tools to optimise tree placement based on the multiple benefits and trade-offs associated with RW.
- Evidence-based coverage targets: Establishing clear, evidence-based targets for tree coverage to guide policy and practice.
- Baseline/localised data: Collecting robust baseline data on water quality, biodiversity to inform tree placement and enable efficient monitoring.
- Need for monitoring strategies: Designing monitoring approaches that effectively capture multiple benefits and trade-offs.

## 4.2 Intra-sector priorities and relevant policy focus

Through the project we engaged with a wide range of stakeholders giving us a broad perspective on evidence requirement to improve practice around RW. Some priorities emerged as cross-sectoral, while other priorities resonated better with certain sectors. In Table 13 we summarise the main evidence gaps that were highlighted as important by specific groups of stakeholders; noting that some gaps overlap sectors. These gaps are linked to specific policies that may benefit from additional evidence on these topics. The topic of monitoring recurred through the stakeholder engagement and led to a dedicated focus group (Appendix 4). In addition, the project identified two sectors linked to both barriers and pathways for RW, namely policy and private sectors, leading to the targeted work presented in Appendix 3 on policy and Appendix 5 on requirements for diversifying funding.

**Table 13. Summary of priorities and evidence topics and their specific sector relevance emerging from the overall stakeholder engagement and reworded by adding nuance from the qualitative responses. This table represent an interpretation of the priority finding and not direct mentions by specific stakeholders. The table also includes examples of policy links to these evidence needs areas.**

<table>
<tr><th>Sectors of relevance</th><th>Summary of evidence topics and sector that could benefit from it</th><th>Examples of specific links to policies and guidance linking to the evidence topics (not an exhaustive policy review)</th></tr>
<tr><td rowspan="3">Health sector</td><td>Data on DOC impacts for drinking water treatment, particularly for private supplies.</td><td>• Need for catchment-scale pollution mapping tools, and explore options for integrating nutrient budgets into initiatives like the Woodland Water Code.<br>• Alignment with River Basin Management Planning RBMP priorities</td></tr>
<tr><td>Frameworks to measure holistic benefits of RW, including mental health. Balancing access to green spaces with ecological integrity.</td><td rowspan="2">• SBS recognises biodiversity's role in human health.<br>• National Planning Framework 4 (NPF4) emphasises urban woodland expansion to improve air quality, manage water, and cool cities.<br>• Scottish Government & Regional Land Use Partnerships (RLUPS) adopt a natural capital approach, integrating climate adaptation, biodiversity, and greenspace creation, potentially extending to blue-green spaces.<br>• Green Health Partnerships (NatureScot) connect health and environment sectors to enhance physical and mental health while tackling inequalities.<br>• Scottish National Adaptation Plan (SNAP3) Outcome one Nature Connects & Place-Based Approaches (NPF4, Outcome 1 & 2) highlight RW as a solution for urban retrofitting, requiring collaboration with local authorities, landscape architects, and designers.</td></tr>
<tr><td>Evidence for integrating RW into blue-green infrastructure to improve air quality.</td></tr>
<tr><td rowspan="3">Private sector</td><td>Baseline data and long-term monitoring to maintain water quality, particularly for water using industries like distilleries</td><td>• RBMP can support and underline that long-term monitoring and research are needed to fully understand the long-term impacts of riparian restoration and large woody material placement on river ecosystems. This includes assessing the effects on water quality, fish populations, and overall habitat health.<br>• Need for catchment-scale pollution mapping tools and explore options for integrating nutrient budgets into initiatives like the Woodland Water Code.</td></tr>
<tr><td>Improved monitoring and evidence on biodiversity benefits for credits. Demonstration sites to secure buy-in.</td><td>• Biodiversity investment plan focuses on these aspects including mapping opportunities for biodiversity enhancement.<br>• The Scottish Government will explore developing an Ecosystem.<br>• Restoration Code to channel private investment into projects that enhance the structure, function, and resilience of ecosystems.<br>• The Scottish biodiversity strategy delivery plan also sets out avenues for monitoring.</td></tr>
<tr><td>Evidence on GHG trade-offs in riparian planting, particularly in sensitive habitats.</td><td>Woodland Carbon Code : It was recognised that WCC doesn't address woodland resilience, a gap that remains in current monitoring of woodland schemes, although the UK Forestry Standard (UKFS) dictates woodland projects must conduct risk assessments to ensure trees are appropriately selected for site and climate conditions.</td></tr>
</table>

| Table 13 continued. Summary of priorities and evidence topics and their specific sector relevance emerging from the overall stakeholder engagement and reworded by adding nuance from the qualitative responses. This table represent an interpretation of the priority finding and not direct mentions by specific stakeholders. The table also includes examples of policy links to these evidence needs areas. | | |
|---|---|---|
| **Sectors of relevance** | **Summary of evidence topics and sector that could benefit from it** | **Examples of specific links to policies and guidance linking to the evidence topics (not an exhaustive policy review)** |
| **Agriculture/land managers** | Economic implications of RW for soil health, productivity, and water availability for crops and livestock. Including evidence of tree species suitability for soils.<br><br>Evidence on long-term RW benefits for farm resilience and profitability in a context of concerns about carbon credits and economic gains. | Nature Connects & SBS DP Support Payments:<br>• Developing a soil security roadmap for Scotland.<br>• Reviewing and updating Scottish Soil Framework.<br>• Creating Soil Health Indicators for Whole Farm Plans, linked to Rural Payments and Services and Forest Management Plans.<br>• Enhancing land manager knowledge on soil erosion risks and mitigation, especially under extreme weather conditions.<br>• Farmers must develop Whole Farm Plans with soil analysis, welfare plans, carbon & biodiversity audits.<br>• River woodlands could support agroforestry, land protection, hay fodder, flood buffers, and erosion control. |
| | Overcoming barriers like financial risks, cultural hesitancy, and tree loss during floods. Improved communication and incentives. | Relevant guidance: The UK Forestry Standard: Creating and Managing Riparian Woodland emphasises the need to assess riparian woodlands' |
| | Practical solutions for managing impacts of beavers/deer and financial risks. Compensation mechanisms for losses (not directly linked to evidence needs). | SBS Delivery Plan Actions:<br>• Action 5.3: Explore ways to support optimal herbivore densities for biodiversity in uplands (Scottish Government, NatureScot).<br>• Action 5.4: Review deer management mechanisms for woodlands and open habitats (NatureScot, Scottish Forestry, Forestry and Land Scotland).<br>Beaver Restoration Policy (Scottish Biodiversity Strategy, 2024):<br>• Beavers recognised as a key ecological component in restored rivers and wetlands by 2045.<br>• Stakeholders emphasise the need for management techniques and ongoing research on beaver population impacts. |
| | Evidence on economic and practical implications of RW integration into farms, with clear guidance and definitions of planting types and benefits. | Relevant guidance: The UK Forestry Standard: Creating and Managing Riparian Woodland emphasises the need to assess riparian woodlands' |
| **Conservation, restoration practitioners and fisheries** | Baseline data (water quality, biodiversity…) and site-specific planting evidence to optimise RW benefits and monitoring. | Cross policy benefit with relevance to development of monitoring strategies and aspects of resilience including SNAP3 Outcome one Nature Connects. |
| | Holistic management approaches, including invasive species roles and herbivore control in riparian zones. | The SBS Delivery Plan (2024-2030) includes actions to 'Develop and implement the Scottish Plan for Invasive Non-Native Species (INNS) Surveillance, Prevention and Control to enable long- term effective INNS removal at scale'.<br>See above on herbivore management. |
| | Evidence on preserving wetland archaeology during RW restoration and managing morphological impacts on sites. | The UK Forestry Standard stresses the importance of protecting the historic environment in forest management planning. As more information is gathered through archaeological surveys and research, it is essential to involve heritage professionals in decisions on woodland regeneration that affect the conservation of cultural and historic sites. |

**Table 13 continued. Summary of priorities and evidence topics and their specific sector relevance emerging from the overall stakeholder engagement and reworded by adding nuance from the qualitative responses. This table represent an interpretation of the priority finding and not direct mentions by specific stakeholders. The table also includes examples of policy links to these evidence needs areas.**

| Sectors of relevance | Summary of evidence topics and sector that could benefit from it | Examples of specific links to policies and guidance linking to the evidence topics (not an exhaustive policy review) |
|---|---|---|
| **Conservation, restoration practitioners and fisheries** | Role of RW in maintaining thermal regimes and aquatic biodiversity, including impacts on fish habitats and temperature. Evidence on fish habitats, shading effects, habitat modification, and optimal RW planting for temperature mitigation. | Further evidence could support the Scottish Wild Salmon Strategy which sets out the vision, objectives and priority themes for protection and recovery. |
| | Evidence on species selection, trade-offs between forestry and ecological benefits, and balancing natural regeneration with planting. | The UK Forestry Standard: Creating and Managing Riparian Woodland emphasises the need to assess riparian woodlands' details aspects of natural regeneration and planting. Further evidence could support update to this guidance. |
| **Environmental regulation and public sector (due to the widespread the remits and expertise of the organisations in this category perception of priorities span a large range of topics that were also relevant to other sectors) we extract here the most recurring topics**. | Tools for identifying pollution sources, pathways, and RW impacts (e.g., on DOC, pesticides, nutrients). Further application of river quality models like QUESTOR in Scotland would be beneficial to understand excessive phytoplankton/algal bloom risks with climate change and how planting of riparian shading in the headwaters is to help with mitigation. | • Scottish Water Climate Change Adaptation Plan 2024 highlights the need for action & investment to: reduce flood and drought risks and protect water supplies from climate change impacts.<br>• See above: Cross policy benefit with relevance to aspects of resilience including SNAP3, Outcome three – Objective 3 focuses on managing Scotland's water resources – building community resilience to flood risk and Outcome two – Objective 3 on community resilience.<br>• Need for catchment-scale pollution mapping tools, and explore options for integrating nutrient budgets into initiatives like the Woodland Water Code.<br>• Alignment with RBMP priorities. |
| | Integration of mapping tools, EIAs, and strategic placement for drought resilience and water scarcity mitigation. Funding barriers. | |
| | Long-term evidence on biodiversity gains, adaptive capacity of tree species, and balancing conservation goals with water scarcity mitigation. | |
| | Evidence on GHG trade-offs in riparian planting, particularly in sensitive habitats. | |
| | Improve mapping of RW to include structure and composition, biogeographical studies, reference condition and metric work to inform the assessment of ecological condition of riparian vegetation and support RBMP monitoring, water status classification and river restoration. | |

## 4.3 Priority topics for future research and knowledge exchange

Section 3.1 concludes with the re-evaluated evidence levels combining the 2022 review with the current review of specific evidence gaps (Table 4). Examining the full breadth of stakeholder input provided insight into patterns of priority-setting across all the benefit areas. The final priority ranking of the evidence gaps per benefit area, accounts for the initial ranking in three clusters from survey and workshop and was adjusted based on qualitative input from interviews and focused engagement (focus groups and consultation). When importance emerged from the qualitative engagement, gaps were moved up in higher priority clusters. No gaps were downgraded in importance.

By combining stakeholder priorities with these evidence summaries, we produce a matrix that identifies priorities for future research and communication (Figure 5, panels (a) and (b)).

**Top priority for research and communication -** Topics which are high priority for stakeholders and where the literature provides only weak to

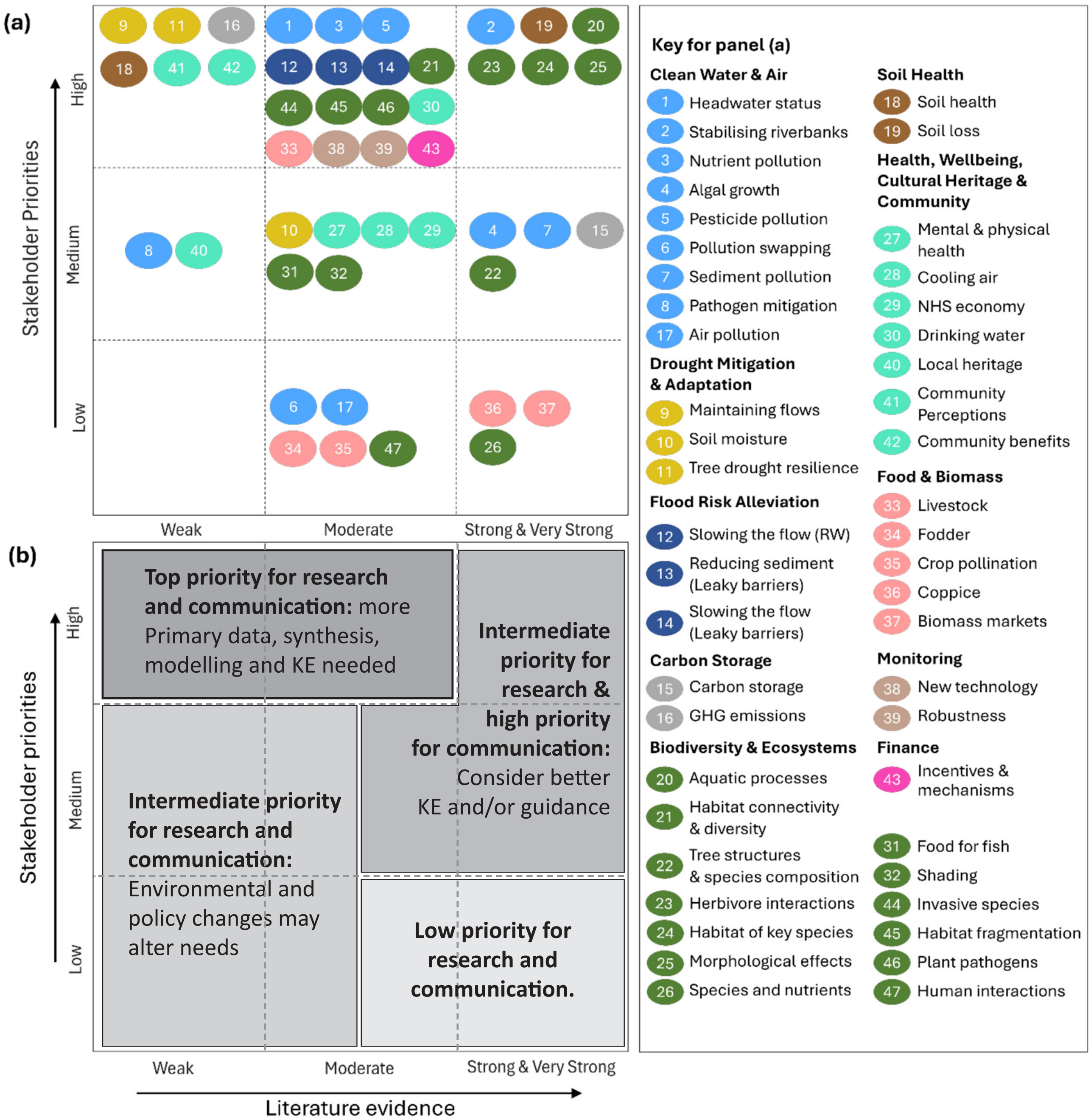


**Figure 5. Overview of stakeholder priorities and supporting evidence. (a) The 47 identified gaps, categorised by benefit themes, as discussed with stakeholders. (b) Recommended priority areas for action based on overall stakeholder input Note: KE = KnowledgeExchange. The matrix positions are based on a review of the specific gaps (x-axis) and the full stakeholder engagement process (y axis). For identification of the specific numbered gaps (1 to 47), see summary text in Table 3 and details in Tables 5 to 12.**

moderate evidence. For all these twenty-one topics more primary data are required, as well as complementary improvements in data synthesis and modelling. These gaps are:

- 9 River woodlands' contribution to maintaining river flows, especially during dry periods.
- 11 Understanding which river woodland tree species can best adapt to drought periods in Scotland.
- 16 The effect of river woodland restoration and creation on greenhouse gas emissions.
- 18 The effect of river woodlands on soil health and structure, biodiversity, fungi and microbes, soil carbon storage and nutrient cycling.
- 41 The understanding of community preferences, social and political perceptions of river woodland restoration.
- 42 How mechanisms for developing restoration projects are socially acceptable, just and beneficial to local communities.

**Intermediate priority for research and high priority for communication** – topics where better understanding is required (High-Medium priority) by stakeholders, but where the evidence review suggests there is strong evidence areas. Topics in this zone to be around communication and guidance. This could also be relevant for gaps with Moderate evidence and Medium priority.

**Intermediate priority for research and communication –** topics where there is currently weak-medium evidence and that are currently low to medium priorities for stakeholders. It is possible that new knowledge from climate and environmental impact scenarios and/or new directions of policy could change demands for information, hence, considering lags in mature knowledge with research process, we urge for a watching brief on these areas and possibly some areas to develop strategic timelines for some future research needs. Actions from (c) to (h) in Table 14 are likely to progress these intermediate areas.

**Low priority for research and communication –** areas of strong evidence with low current stakeholder priorities are at the lowest priority for, or do not need, additional research. This may also be extended to low priority areas with moderate evidence and potentially to topics with both moderate priorities and evidence levels.

For sectors and organisations who are relatively ‘new’ to RW, which is true for many private sector organisations, it is likely that they may be unaware of existing information or only have only a partial understanding of a topic. This makes knowledge exchange between academics, communication of knowledge to practitioners and other stakeholders and guidance and implementation tools (Table 14) vital to all aspects irrespective of their formal state of academic evidence.

## 4.4 Pathways to working with evidence to support action for river woodlands

It is important to recognise that each evidence gap generates specific research questions, each requiring a tailored approach to being addressed. However, Table 14 outlines general pathways shaped by stakeholder input, that will enable translating research into impact and scientific knowledge, with progress moving from early-stage research at the top to mature findings at the bottom. To address topics in the green sector of Figure 5 (high prioritisation, weak-moderate evidence) we must start at the activities at the top of the table and work downwards progressing impact. The delay in deriving insights and achieving impactful outcomes from research on weak evidence topics should be acknowledged; the impact pathway may require significant time to produce well-developed outputs, such as guidance and implementation tools. Conversely, topics in the top right of Figure 5 (where there are high priorities with strong existing evidence) may already be further down the impact pathway and will more quickly help accelerate RW implementation. Table 15 takes the top left sector of Figure 5 (limited to high priority, weak current state of evidence) and develops example of medium-long term feasible research pathways and building on the research impact progression in Table 14. Whilst drought topics appear in this highest ranking by virtue of weak evidence, we stress the importance of combined system research on hydrological extremes (floods and droughts).

To ensure research is practically relevant and effectively supports policy development, specific research projects should be co-designed with stakeholders from the outset. This approach will help align studies with real-world challenges, increase applicability for land managers and practitioners, and ensure outputs are actionable within existing governance frameworks. Research initiatives should also adapt to funder priorities while maintaining scientific rigor and institutional relevance, balancing policy-driven needs with long-term knowledge generation. For example, ongoing policy developments, such as efforts to harmonise soil policy and regulatory frameworks, highlight the need for research that directly informs better guidance, surveillance, and implementation. Furthermore, strategic partnerships with existing networks, such as the Riverwoods Initiative and Catchment Partnerships, can enhance impact by leveraging their broad oversight across multiple benefit areas. Organisations with specialized restoration expertise, such as fisheries bodies and River Trusts, should also be engaged to integrate species-specific insights into wider ecosystem restoration efforts. The database (Appendix 6, tabs 6a, b) explores funders and funding schemes. This exercise of compiling these has shown there are multiple funders who may fund technical developments as well as practice. Funders such as UKRI have schemes (sometimes strategic, others open 'Discovery' science) of relevance to RW but do not fund implementation, so studies must use existing implementation case studies but risk short durations not having robust conclusions for aspects where tree growth is required. Other schemes, for example EU LIFE and Interreg, are conversely about change on-the-ground but less details, if any, of the evaluation of outcomes and especially mechanistic process knowledge or model development. Since funding calls are specific and as yet unknown, or open 'Discovery' science it is hard to make funder and funding scheme recommendations specific to topics or generally. However, there is enhanced value in longer-term data collection and funding alignment to RW outcomes in practice or policy-development. For this government funding may be best aligned.

<table>
<tr><th colspan="2">Table 14. Activities in the pathways to resolve priority evidence needs.</th></tr>
<tr><th>Activity steps and purpose</th><th>Study specific points</th></tr>
<tr><td>a. Address funding gaps: Justify public/ private investment in research by linking it to ecosystem protection, governance, and policy needs. Time-sensitive topics (e.g., droughts) can drive funding, and demonstrating combined benefits will attract more support.</td><td>Economic feasibility and incentives: Concerns over costs, especially in agriculture and community adoption, highlight the need for evidence-based financial incentives.</td></tr>
<tr><td>b. Build missing primary data: Controlled experiments and monitoring are needed to isolate RW effects from broader landscape influences. Key targets are outlined in updated reviews (Figure 4, Table 13).</td><td rowspan="4">Need for localised, context-specific evidence:<br><br>Stakeholders require tailored data to improve confidence and address environmental variability.<br><br>Evidence gaps on trade-offs and synergies: Research is needed to assess competing objectives (e.g., carbon vs. methane, biodiversity shifts, drought adaptation vs. water retention).</td></tr>
<tr><td>c. Coordinated monitoring of practice: Strengthen evidence from river restoration projects with structured citizen science, robust metrics, and data synthesis.</td></tr>
<tr><td>d. Collate datasets nationally and resolve data consistency issues: This involves being effective at monitoring outcomes of woodland implementation projects and bringing data together for best impact through modelling and other data synthesis. Collection of data that is incoherent within and across studies (or national monitoring) hampers knowledge creation.</td></tr>
<tr><td>e. Develop modelling: Mature research (good quality data across scales, appropriate durations for effects etc) allows data to be compiled for developing, validating models and then running scenarios, for example future environmental change impacts-intervention outcomes or upscaling of effects.</td></tr>
<tr><td>f. Build KE structures between academics: Biophysical benefits (e.g., flood/drought impacts) should be studied together, integrating soils, water, air, and biodiversity. Social-biophysical interdisciplinary research is key for cost-effectiveness, green finance metrics, and community impact assessments. EU COST Actions (e.g., CONVERGES) provide strong models.</td><td>Holistic and multifunctional approaches:<br>To account for the interconnected nature of ecosystem benefits, integrated tools should assess multiple benefits (carbon, biodiversity, soil health, flood mitigation) rather than isolated impacts.</td></tr>
<tr><td>g. Communication of knowledge to practitioners and other stakeholders: Synthesised scientific knowledge should be audience-targeted, providing actionable thresholds and clear outcomes for stakeholders.</td><td>Stakeholder involvement and co-creation [also links to step c]: stakeholders stress the need for transparent communication on benefit and trade-off of interventions, co-creation of project, and community involvement, opportunities like citizen science. This resonates across all themes and across majority of stakeholders. Co-creation was also mentioned by private finance stakeholders as crucial for ensuring that projects are tailored to often very specific needs of investors.</td></tr>
<tr><td>h. Build guidance and implementation tools: Co-produced scientific knowledge can drive iterative guidance and decision-support tools (e.g., multi-criteria mapping of riparian pressures).</td><td>Stakeholder involvement and co-creation [also links to step c]: stakeholders stress the need for transparent communication on benefit and trade-off of interventions, co-creation of project, and community involvement, opportunities like citizen science. This resonates across all themes and across majority of stakeholders. Co-creation was also mentioned by private finance stakeholders as crucial for ensuring that projects are tailored to often very specific needs of investors.</td></tr>
</table>

**Progression towards more mature research, better tools and implementation practices**

**Table 15. Examples of recommended pathways for future research and impact, forwards on for the six topics considered high priorities by stakeholders and low level of evidence (Top left of Figure 5), including feasible medium-long term action steps.**

| | **Benefit areas** | **Water stress and drought** | | **Carbon** | **Soil health** | **Health, community, heritage** | |
|---|---|---|---|---|---|---|---|
| | Top priority gaps with weak evidence | 9 | 11 | 16 | 18 | 41 | 42 |
| | | ***RW effect on river flow during dry periods*** | ***Drought tolerance of tree species*** | ***RW effect on GhG (emissions specifically)*** | ***RW effect on soil health and structure*** | ***Community preferences and perceptions of RW restoration*** | ***RW socially acceptable, just and beneficial to local communities*** |
| **Research and impact activities** | Identification of appropriate research funding (see Appendix 6) | | | | | | |
| | Step 1: Primary/ baseline data | Evidence at larger scales & where RW changes dominate other catchment signals; Floodplain water storage | Data on tree species drought and multi-stressor interactions | Riparian monitoring in GHG studies; Link data to soil mapping. | Derive key indicators for UK soil health; Study outcomes with RW management across diverse soils | Investigate attitudes to RW restoration & management (e.g herbivore control). | Investigate co-benefits & trade-offs of RW access; Research barriers to uptake of RW by communities and businesses not yet involved |
| | Step 2: Data collation, synthesis, modelling | Coordinate monitoring practice; Develop model & scenario predictions. | Model tree species drought resilience vs benefits | Model links between riparian terrestrial & aquatic compartments. | Guide riparian specific soil monitoring | Develop practice and tools that maximise social benefits & raise awareness | |
| | Step 3: Knowledge exchange, tools & guidance | KE between academics; Communicate knowledge to practitioners | KE on RW vs other land use (wetlands and uplands) | Improve carbon inventories specific to RW (e.g. fallen/ dead wood) | Generate knowledge for soil policy development | Communication of knowledge between academics, practitioners and public | |

**Enabling through monitoring**

Addressing evidence gaps in RW restoration requires robust research and long-term monitoring. Both SNAP3 and its Monitoring and Evaluation Framework emphasise the importance of sustained data collection to assess RW impacts effectively. As part of this project, a focus group of environmental monitoring experts developed collective recommendations on how monitoring should be better targeted, implemented, coordinated, and promoted to generate reliable evidence. Their findings, including the 10 Recommendations for Improved Riparian Woodland Monitoring, are detailed in Appendix 4 and a summary of the recommendations is available in section 4.6. Key priority areas for evidence collection include:

1. Assessing RW effectiveness—such as reach-scale impacts of instream large wood, shading and cooling effects, and flood peak mitigation.
2. Understanding the timescales required for RW benefits to materialise across different river types.
3. Evaluating the effectiveness of various woodland creation methods.
4. Identifying and addressing potential conflicts, including biodiversity targets, access, and infrastructure.

A recurring challenge is understanding RW impacts at a larger scale (Figure 6). The role of RW in mitigating flood risk, low flows, and water quality is widely recognised, but isolating its specific effects remains difficult. Our review identified several studies assessing mitigation measures at scale, yet most struggled to attribute outcomes directly to RW. One way to address this is through intensive, localised monitoring that isolates RW effects, which should be integrated into a broader multi-scale monitoring strategy.

The data gathered from such localised studies could be used to refine modelling processes, improving parameter accuracy and reducing uncertainties in large-scale assessments. Validating these models against broader catchment datasets would further enhance reliability. Implementing a *catchment laboratory approach*, particularly in areas where RW projects are being planned, could be a practical method to achieve this.

Beyond increasing monitoring efforts, leveraging new analytical and technological advancements is essential for efficiency and accuracy. Emerging tools such as eDNA, AI, LiDAR, and acoustics provide innovative ways to enhance data collection. Stream restoration projects, in particular, should develop tailored monitoring plans that align with their objectives, whether for accountability, effectiveness, or management. These plans should define success metrics, expected recovery timescales, and resource allocation, ensuring clarity on data collection, management, analysis, and sharing.

Citizen science also holds significant potential for RW monitoring. Initiatives such as the Riverfly Partnership (led in Scotland by Buglife's Guardians of Our Rivers), Smart Rivers, and MoRPH are helping to build a citizen-led equivalent of the Water Framework Directive (WFD) testing for river health. However, ensuring the reliability and utility of citizen science data requires structured training, quality control, and standardisation, as in mainstream research and regulatory monitoring.

Despite extensive data collection efforts, much of the information remains inaccessible or lacks standardisation. Scotland's Flood Resilience Strategy (SNFRS) aims to improve flood resilience through better data use, but a more coordinated approach is needed. Establishing a centralised, open-source data repository could enhance data sharing and meta-analysis, supporting more informed decision-making. While this would be a long-term

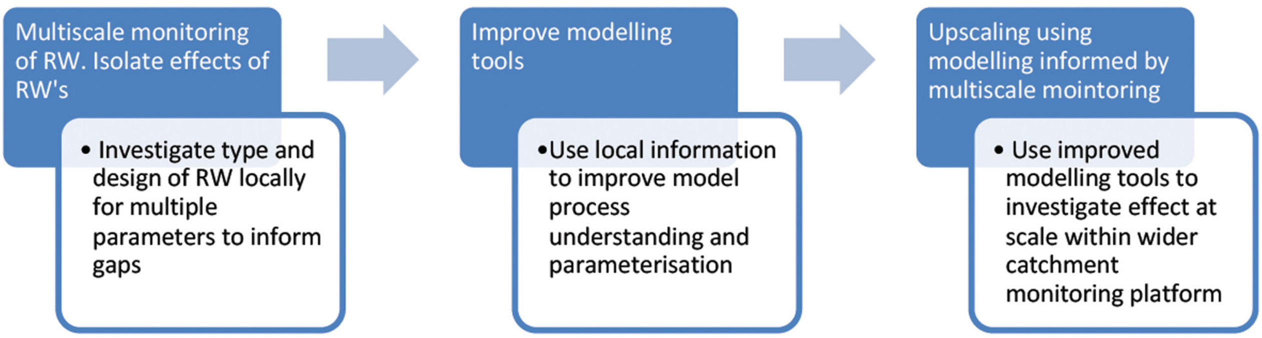


Figure 6. A recommended sequence of activities for enabling effects to be predicted at appropriate scales.

commitment, it would provide a vital platform for consolidating and utilising RW-related evidence.

Investment in standardised monitoring is crucial to demonstrating RW benefits, which in turn can help secure policy and funding support. The Scottish Government recognises the need for resilient ecosystems, and clear, evidence-based monitoring could strengthen the case for increased investment. Additionally, several groups are exploring crediting mechanisms, such as the *Woodland Water Code*, to attract private investment by valuing the ecosystem services provided by RW.

**Diversifying funding as pathway**

Sustaining and diversifying sources of funding for RW was reported as a critical area by multiple stakeholders. Many sectors may benefit and depend on the benefits provided by RW; however, they may not be fully aware of the value for their business or operation.  Therefore, communication of pre-existing evidence will be important to help diversify funding.  Such communication must be targeted to specific sectors, as precise evidence needs will vary according to the operational model of different sectors and businesses. The results of our consultation on diversifying funding for RW are available in Appendix 5.

Examples of potential sectors to target are those whose business directly depend on access to high quality water, including but not limited to Whisky distilleries. A recent CREW project on the challenges of future water scarcity and drought (Glendell *et al.,* 2024) where predictions of increased future frequency of low flows are motivating engagement by distilleries and agricultural sector representatives showed that it is not always necessary to 'price' the values of RW; what is necessary is to convince businesses that they will benefit from, or depend on RW. Evidence is also needed to support landowner engagement by demonstrating the benefits of riparian practices and developing financial incentives or compensation mechanisms. Further, the establishment of standards for nature finance markets and compensatory schemes is a key area for future research. The Riverwoods Investment Readiness Pioneers project exemplifies efforts to advance nature-based financing solutions by connecting diverse stakeholders (communities, landowners, and investors) to explore innovative funding mechanisms beyond traditional grants.

Scotland's evolving natural capital market presents opportunities for private investment in RW, particularly through emerging biodiversity and ecosystem restoration finance mechanisms. Currently, investment is primarily driven by carbon markets, such as the WCC and Peatland Code, which fund woodland creation and peatland restoration. However, broader ecosystem restoration codes are in development, aiming to attract responsible private investment into a wider range of habitats, including riparian woodlands (Natural Capital Market Framework). To further expand investment opportunities, the Scottish Government is developing an Ecosystem Restoration Code, which will provide high-integrity governance, monitoring, and verification for biodiversity projects. This aligns with efforts such as the Taskforce on Nature-related Financial Disclosures (TNFD), which is expected to drive corporate demand for voluntary biodiversity markets (SBS Delivery Plan).

Additionally, the newly published Biodiversity Investment Plan points to funding mechanisms like the Private Investment in Natural Capital (PINC) programme and the Facility for Investment Ready Nature in Scotland (FIRNS) aim to connect private and public investment with nature restoration projects. These initiatives could provide financial pathways for RW projects, particularly if integrated into Scotland's broader biodiversity investment strategy (Biodiversity Investment Plan).

## 4.5 Methodological reflections and future work

The methodology and outcomes of this project offer insights to other applications in catchment and habitat restoration, such as wetland or peatland restoration, when seeking to refine and prioritise evidence gaps. Stakeholders have varied understanding and perceptions of the wide range of literature and evidence topics linked to RW, and this is certainly also the case for other topic areas. The literature review process was essential, reviewing ~60 topics over a decade of scientific and grey literature. While search terms structured the review, selecting the five most relevant papers from large, often redundant search returns demanded expert judgment to capture the breadth of each field. Documenting inclusion criteria was crucial for updating the evidence base and assessing the strength of evidence. This was central to assessing alignment and misalignment with stakeholder priorities which contributed to our prioritisation of evidence and some core pathways to address them (Figure 5). Stakeholder engagement complemented the review by integrating both deductive (predefined gaps) and inductive (open-ended) approaches. Combining these methods proved essential to capturing diverse perspectives. We recommend using discursive methods which produce qualitative data and also foster interaction between participants: this can support social learning, which is valuable in its own right and also helps to reveal and clarify doubts about the topics and underlying evidence. It was challenging to collect views from stakeholders who are not currently well-engaged in working for RW, yet who could be relevant. We partially mitigated this through targeted recruitment, using their preferred platforms and means of engagement but we could not engage all those potentially relevant. If this is a priority for future work, then specific projects targeted at specific stakeholder groups are probably required to increase understanding of their viewpoints.

**Future research:**

- **Targeted Reviews:** Now that stakeholder priorities are clearer, future efforts should focus on specific evidence gaps and refining research question to develop practical tools and decision-making resources. This should involve collaborations between researchers and potential stakeholder benefiting from those tools.
- **Beyond evidence gaps:** Lack of evidence is often not the main barrier to action—funding, interest, and institutional constraints often play a greater role. Prioritisation exercises should contextualise gaps within these broader challenges.
- **Actionable knowledge and uncertainty:** Rather than seeking absolute certainty, research should emphasise practical, well-monitored actions that support RW restoration despite inevitable uncertainties.
- **Engaging sectors that are not yet involved:** Consensus in priorities across such a range of topic and stakeholders is of course impossible. What is aligned with a key business interest for one sector will not be for another - so this may strengthen the rationale for projects targeted to specific stakeholder groups to understand their specific needs and increase uptake of RW. Such focus sectors or stakeholders could be: farmers, landowners, human health and mental health stakeholders, local heritage and archaeology stakeholders.

## 4.6 Overall recommendations

The following recommendations are drawn across all research phases (including details in Appendices 2 to 6). These activities aim to enable addressing priority R&D needs as well overcoming barriers to RW restoration. We consider these in five overlapping areas: research, policy, funding, monitoring and coordination.

### Build interdisciplinary research effort and common platforms:

- **Expand biophysical evidence** on the effects of large wood in rivers, shading and water cooling, flood peak reductions, conflict potential with other biodiversity objectives, pollution swapping, drought mitigation and soil health (see Figure 5 for specific weak evidence gaps with high priority). Ensure the effect size in studies (i.e. proportion of RW intervention) fits the desired outcomes and studied indicators to deliver robust conclusions separating RW from other catchment aspects.
- **Commence interdisciplinary study trials** on the effectiveness of various RW targeting, scaling and management methods.
- **Combine social studies with biophysical aspects** to advance community preference needs, cost effectiveness, benefits valuations towards improved finance methods.
- **Integrate existing knowledge** to provide actionable tools for practice such as tree placement and coverage mapping to optimise design that will foster multiple benefits.
- **Consider holistic benefits within riverscapes** by considering packages of measures need to achieve a restored riverscape and promoting combined study of these. The obvious example is combining research on hydrological extremes (across floods and droughts) but this becomes further improved as part of a larger system of water-air quality, habitat, social aspects etc, as well as likely saving research costs over separate trials.
- **Undertake research to determine:** a) best practices for responsive indicators of change, b) timescales for benefits accrual, c) river typing towards understanding reference conditions and anticipated trajectories of change.
- **Develop screening tools to identify the optimal siting and extent of new river woodlands,** and to assess their potential contributions to ecosystem services over time, could be enhanced by research that makes use of tools such as LiDAR mapping and advanced spatial modelling. This should build on research examining RW targeting approaches, scales of intervention and management trials. Tools must be transparent in the models/assumptions behind them and limitations.

### Shape policy to recognise specific riverscape needs:

- **Policy targets for river woodland:** Relevant policies should align and provide viable targets for RW coverage and be guided by the information contained in the 2022 and updated reviewing here. Agreed policy objectives are needed to provide a clear roadmap for stakeholders and enable coordinated and focused efforts.
- **Policy targets for soils and habitats specific to riparian zones,** giving specific recognition to the critical transitional ecosystem role and functions and with onus on specific monitoring/ data collection and protection.
- **A critical need exists for cross-policy integration** to align diverse and sometimes conflicting agendas, such as flood management, biodiversity conservation, and agricultural resilience. At the forefront is the development of integrated frameworks that unify evidence and solutions across local, regional, and national scales. Adopting a systems-based approach will facilitate collaboration among key stakeholders, enabling them to co-create strategies, understand interconnections between challenges, and identify necessary compromises or mutual benefits. For example, organising regional events followed by a national policy conference could serve to combine outputs, share insights, and foster alignment. These initiatives should prioritise actionable outcomes, incorporating elements such as financial considerations, policy alignment, regulatory frameworks, and sectoral implementation. Discussions and decisions must be clearly documented to ensure they are accessible and comprehensible for both participants and external audiences.
- **Adaptive management** strategies are needed to balance these scales and ensure that policies address both broad and localised priorities effectively.

### Diversify funding:

- **Develop and promote sustainable finance models,** including green financing and carbon markets, to unlock resources for large-scale restoration initiatives.
- **Establish stronger and more effective regulatory frameworks for natural capital markets** and diversifying funding mechanisms. Sustainable finance models, including carbon markets, can unlock resources to support large-scale RW initiatives while ensuring accountability. These can benefit from improved metrics and indicators, valuation of benefits and accreditation for wider aspects than carbon-based accounting.
- **Provide and communicate evidence tailored to the needs and business models of diverse private sector organisations**, helping them understand the benefits of RW restoration and reduce perceived risks. Communicating existing information is a priority, as many private sector organisations relatively new to RW restoration may be unfamiliar with the existing state of knowledge.
- **Facilitate networks** that bring together public, private, and research sectors to share insights and strategies to improve the funding environment to support RW restoration.
- **Co-create projects** to align with the priorities and interests of corporate funders, ensuring they address specific geographic and sectoral needs.

### Refine monitoring and make the data work harder for the investment:

- **Ensure clarity on the purpose of monitoring:** particularly whether monitoring is required for accountability or effects. Design monitoring programmes according to the questions to be addressed.
- **Long-term monitoring programs that assess resilience, biodiversity outcomes, and climate impacts are required to support adaptive learning and iterative policy refinement.** By tracking progress and outcomes, stakeholders can make evidence-based adjustments to optimise effectiveness.
- **Implement findings of research towards better monitoring** on responsive indicators, river type-specific reference conditions, timing and trajectories of change.

- **Develop, utilise and promote technical advancements:** a) monitoring of dead wood transported in rivers, b) environmental DNA techniques, c) use of AI data and remote sensing data (satellite, aerial imagery, LiDAR).
- **Establish catchment observatories** for robustly investigating key questions. Seek to consider larger physical scales and longer time periods. As this is complicated by shifting environmental baselines, the needs for consistencies in controls, methods and funding need to be considered.
- **Expand and support well-trained and coordinated citizen science programs** to generate high quality, evaluated data as well as foster community involvement in RW.

### Coordinate across national initiatives, promote needs and benefits and advance practice:

- **Coordination of widespread new data** towards enhancing scientific studies with national synthesis of practitioner project outcome assessment and modelling using common metrics and some training to support robust data collection
- **Create knowledge resources and guidance:** Create and maintain a list of guiding literature plus a range of examples and case studies for developing state of the art RW restoration. Select projects to develop guidance for best practice. Coordinate development of guidance across stakeholders' guidance needs, examples of what's worked and what not against examples of practice in different parts of the UK.
- **Further national profiling of the need and benefits of RW** by a coordinating body such as Riverwoods Initiative (SWT-led).
- **Stakeholder collaboration remains fundamental to success:** Strengthening partnerships among policymakers, landowners, researchers, and local communities will foster the exchange of knowledge and build trust. Peer-to-peer networks can play a pivotal role in disseminating best practice and encouraging increased uptake of sustainable approaches.

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