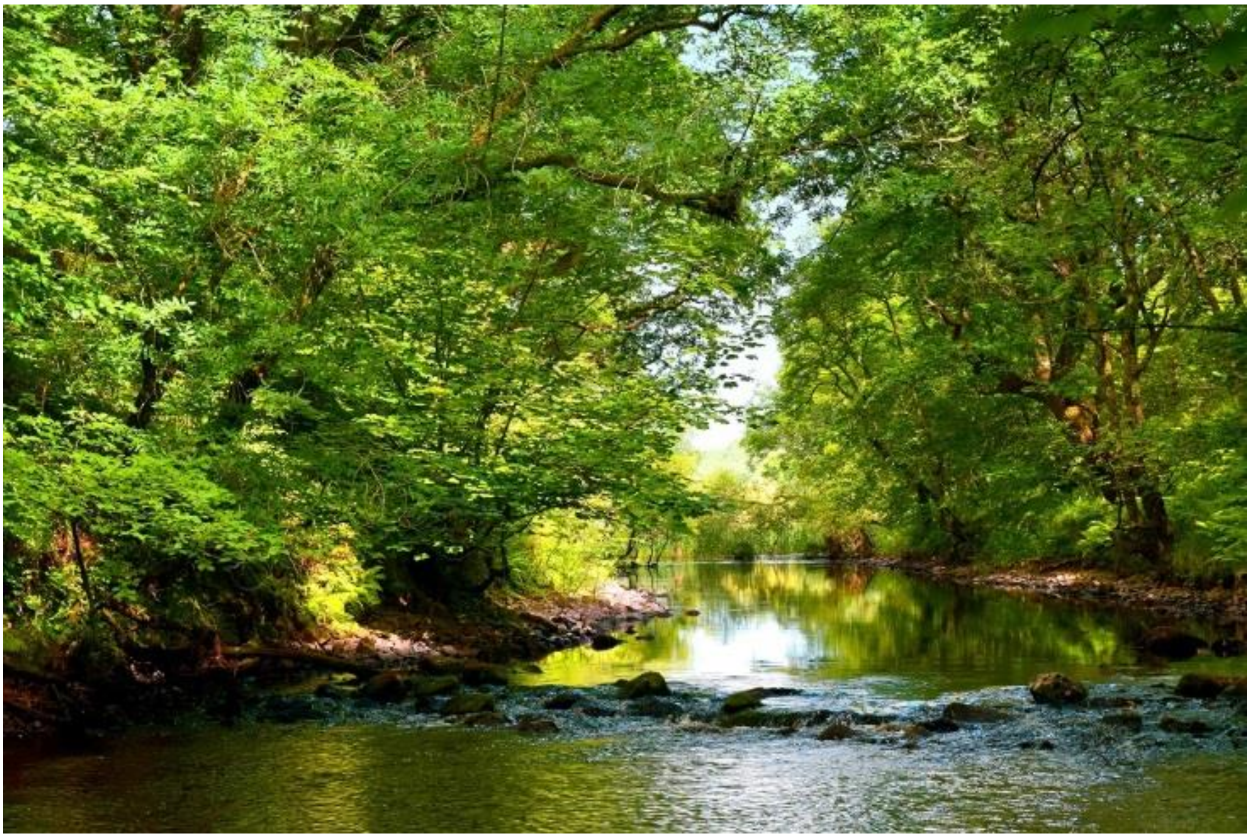
Riverwoods for Scotland
Report on Scientific Evidence



The Riverwoods Science Group

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Contents

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- Minor editorial changes to spellings of “river wood” and “river woodland” throughout the document.
- Minor editorial changes to “riverscape” and “landscape” throughout the document.
- Minor edits to “Next steps”.
- Section 1.1, para 2 now: "the Scottish Wildlife Trust".
- Section 1.1, para 2 now: "Scottish Nature Finance Pioneers"
- Added Riverwoods website.
- Edwin T and Peter C in the acknowledgments.
- Change to “initiative” now not capitalised.
- Removed DOI: http://dx.doi.org/10.13140/RG.2.2.28753.61284
- Uniform “Evaluation of evidence” heading through section 3.

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Executive summary

The Riverwoods initiative

The goal of the Riverwoods initiative (riverwoods.org.uk) led by the Scottish Wildlife Trust is to create a network of river woodlands supporting healthy and resilient river systems across the whole of Scotland funded by a diversity of financial sources including private and public funding.

Why invest in restoring river woodlands?

River woodlands are essential for healthy rivers and provide multiple benefits which help tackle the twin biodiversity and climate crisis. A SEPA project, including field surveys from 2015-16 found that over 50% of riparian vegetation on Scotland's baseline river network is in poor condition without any trees or shrubs. Restoring Scotland's river woodlands is a priority and a key candidate for funding under conservation finance initiatives as a nature based solution. Collating the available scientific evidence on the benefits of river woodlands provides an evidence base to justify financial investment in river woodlands for society, the economy, and nature itself.

Many of Scotland's rivers are completely bereft of the natural woodlands and vegetation communities. River Dee at Braemar. (Credit: Roberto Martinez SEPA)

Key aims of the evidence report

1. To provide a broad indication of the most up-to-date scientific evidence underpinning the environmental benefits that river woodlands provide for Scotland.
2. To present quantified evidence of river woodlands functionality.
3. To classify the strength of the evidence based on the quality of studies to provide a level of confidence in woodland measures for investment purposes.

Audience & beneficiaries

The evidence in this technical science report will be valuable to a range of users including financial investors, businesses, land and river managers, Scottish Government and its agencies. The beneficiaries for specific benefits have been outlined in each benefit section.

River woodlands provide many benefits to people such as providing clean water, supporting health and well-being and sustainable food production. (Credit: IMG Dugan)

River woodland types

The river woodland types included in the review are native riparian woodlands, floodplain woodlands, man-made riparian woodland buffers, gorge woodlands, natural large woody material and man-made large woody structures.

Results

A summary of the strength of evidence for river woodlands is presented in the table below. The strength of evidence is based on the quality of studies for each of the functions, with functions grouped into the benefits that river woodlands can deliver (column 1). The strength of the evidence ranges from very strong to weak. The majority of functions indicate a moderate to strong level of functionality based on empirical data quantifying a positive effect.

River woodland Benefit	Strength of evidence for functions of river woodlands			
	Very strong	Strong	Moderate	Weak
Clean water	Stabilising riverbanks	Controlling nitrogen pollution Controlling phosphorus pollution Controlling excessive algae & periphyton Capturing sediment pollution Capturing pesticides		Capturing pathogens
Conserve Biodiversity & Ecosystems	Supporting aquatic processes	Supporting other species 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 Reducing coarse sediment delivery and siltation of channels	
Climate action: Carbon			Carbon sequestration & carbon storage	
Clean air		Capturing air pollutants		
Sustaining soils		Reducing soil loss		Improving soil health
Good human health		Exposure to river woodlands 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 Providing shelter & shade for livestock	Providing fodder for livestock	
Clean energy Biomass		Provision of biomass for energy		

Conclusions & recommendations

Specific recommendations have been provided for over-arching themes in the report and for healthy and resilient river systems and benefits to people (section 4.0). The key messages for the over-arching themes are as follows:

Design & location: River woodland measures need to be established with appropriate design and management to be effective and should be placed strategically within the catchment, in the right location(s) and at the right scale as this is critical for the delivery of the benefits.

Landscape scale approach: A landscape scale approach will improve delivery of many of the benefits and especially for clean water and flood alleviation. Sediment eroded from banks is often not a major source of polluting fine sediment, compared with sources direct from cultivated land.

Component of sustainable integrated land management: Land-use management has an impact on the quality of soil, air and water. River woodlands help safeguard our environment, whilst providing climate change resilience and diversification on farms. They also provide an income and support agricultural production via carbon, pollination, biomass and agroforestry.

Component of Scotland's Nature Networks: Establishing a network of riparian and floodplain woodlands enables nature to adapt to climate change by supporting reproduction and genetic diversity of species and species migrations. River woodlands will also contribute to biodiversity on a landscape scale as an important component of a heterogeneous landscape.

Improve evidence: Improved evidence at catchment scale and over longer timescales will improve confidence in river woodlands as a nature-based solution. Estimations on the time it takes for benefits to be realised will be valuable for catchment planning, for example in identifying future needs of drinking water supplies or flood risk changes.

Next steps

1. Communications work is required to tailor the scientific evidence for specific audiences, including the buyers and suppliers of river woodland ecosystem services. Plans are in place to deliver some of this through the Riverwoods partnership.
2. A business case needs to be developed to enable effective delivery of river woodlands under the Riverwoods initiative, underpinned by bespoke business plans for each Riverwood project. This is being addressed through the Riverwoods Investment Readiness Pioneers project being funded by the Esmée Fairbairn Foundation.
3. Demonstration sites should be developed to show the pathway to investment ready projects and reduce uncertainty about outcomes for investors. Early work on this has now begun.
4. The time that it takes for trees to establish to provide specific functions and benefits should be analysed and collated as it is an important consideration for investment and benefit calculations.
5. Further work is required to review the most up to date decision support tools and guidance for implementation.
6. River woodland benefits should inform codes and standards supporting the development of natural capital markets and the shift towards a nature positive economy.
7. This evidence report has identified a number of research and development gaps for river woodland implementation which should be assessed for prioritisation depending on business requirements.

1 Introduction

1.1 What is the Riverwoods initiative

Riverwoods is an ambitious initiative launched in early 2019, to create a network of river woodlands which supports healthy and resilient river systems across the whole of Scotland.

The Riverwoods initiative is led by the Scottish Wildlife Trust. It brings together a wide range of partners to identify where riparian woodland can be better managed and lost woodland corridors recreated. A nation-wide programme to create and restore river woodlands relies on funding from diverse sources. Working together on the £Billion challenge route map[1], the Scottish Nature Finance Pioneers are exploring how existing financial mechanisms such as grants, philanthropic giving, and sources of private finance can be combined to develop blended finance solutions to support Riverwoods delivery.

The report has been developed by the Riverwoods Science Working Group of the Riverwoods initiative to provide scientific evidence of the benefits of river woodlands to inform further work with investors, land managers and local delivery partnerships.

The evidence supports the creation of a network of river woodlands as a nature-based solution that addresses climate change and provides multiple benefits to society. It also identifies the limitations and gaps in current knowledge.

1.2 Why are river woodlands needed?

Streams and rivers within catchments are physically connected, running from the headwaters of their source to the sea, and laterally within their floodplains. The physical connection and the plants and animals within the water environment are important for the provision and processing of energy changes down the length of the watercourse. The provision and processing of energy changes from the top to the bottom of this chain, and laterally on the floodplains with flow pulses such as floods. A river woodland is essential for freshwater ecological functioning, carbon and nutrient recycling, enabling a healthy river system. The role of river woodlands in supporting a healthy river system is in section two of this report.

In Scotland, the native trees and woodlands along these streams and rivers have largely been removed through intensification of agriculture, urban development, or damaged and prevented from regenerating by browsing and grazing animals (Smout, 2003). The impact of these changes on riparian vegetation quality is summarised in Box 1, see section 2.2.1 for details of classification.

Box 1: Riparian vegetation condition

Based on SEPA's 2015/16 morphological surveys of river channels and riparian bank vegetation together with remotely surveyed data covering the baseline* river network the condition of the riparian woodland vegetation is:

56% of the bank length is in **poor** condition.

11% is in **moderate** condition.

13% is in **good** condition.

20% of the bank is adjacent to other non-woodland habitats** (wetlands, peatland, etc).

*Baseline rivers are those river water bodies with catchment size >10km². The ecological condition of these water bodies is reported as per Water Framework Directive and RBMP objectives. The length is ~27,000 km (21% of Scotland's digital river network ~125,000 Km).
**More work is required to assess the naturalness and condition of these habitats.

[1] Trust and SEPA publish route map towards £1 billion for nature conservation – Scottish Wildlife Trust

Other modifications to rivers that enable human activity affect river continuity, separating rivers from their riparian zones and fragmenting the river's ecological functions, including the extent of benefits that river woodlands provide. A Europe wide survey, including rivers in Scotland, found that many of these barriers are under recorded (61%) with 68% of structures less than 2m high. Most of the barriers in Europe's rivers are structures built to control and divert water flow or to raise water levels, such as weirs (30.5%), dams (9.8%) and sluice gates (1.3%); to stabilise riverbeds, such as ramps and bed sills (31.5%); or to accommodate road crossings, such as culverts (17.6%) and fords (0.3%) (Belletti, *et al*., 2020). Whilst some of these structures are historic and redundant, fragmentation continues e.g. hydropower installations with reservoir dams, weirs and channelisation, which separate rivers from their natural paths and riparian zones, have affected the connectivity of river networks (Addy *et al*., 2016).

The Water Framework Directive and European Biodiversity Strategy aim to address this, by supporting the concept of free-flowing rivers, where feasible. This includes not only the removal of barriers for fish but also restoring natural processes; allowing rivers to use their floodplains, encouraging groundwater recharge and healthy beds, banks and adjacent zones of influence. People restoring river woodlands need to consider river connectivity and restoration of natural processes if they are going to fully benefit from restoring river woodlands.

It is proposed that restoring a network of rivers and their associated woodlands will help address climate change and its impacts on our businesses and human well-being. Climate projections show that Scotland can expect warmer, wetter winters and hotter, drier summers. Extreme weather is likely to become more variable and more frequent, leading to greater risk of both droughts and floods. Modelling predicts increasing flow peaks of roughly 50% on average by the 2080s (Kay *et al*., 2019a). Drought projections show that extreme drought events are likely to increase across Scotland from the baseline data (1981-2001) of one every 20 years to one event every three years (2021-2040) (Kirkpatrick Baird *et al.,* 2021). Drier summer months will put river catchments under more pressure from abstractions, reducing the resource available for water users. Lower summer flows will also reduce the ability of rivers to dilute pollutants with the possibility of increased treatment costs for dischargers. Therefore, this report considers the role of river woodlands in mitigating climate change.

The report addresses the role of river woodlands in adapting to changes in water temperatures, which is a threat to fisheries and biodiversity in Scottish rivers. Water temperatures of 27°C and 25°C were recorded in Scotland in 2013 and 2014 (James Hutton Institute, 2019; Pohle *et al*., 2019). In 2018, 70% of Scotland's rivers experienced temperatures that would cause thermal stress in Atlantic salmon (>23°C) (Jackson *et al.*, 2020). Climate change projections under UKCP18[2] suggest that summers like this will occur every other year by 2050, where high temperatures will be exacerbated by low flows. With an expected increase in air temperature of 4°C by 2080, there are concerns about the potential impact on Scotland's cold water-dependent fish populations and other species, and the consequences for rural economies, as well as the health of rivers.

The wide range of benefits to people from river woodlands both now and in the future are described in detail in section 3 of this report. The evidence of the functions provided by river woodlands is assessed and strength evaluated.

1.3 River wood definitions

River woodlands include trees, woodlands and forests, both natural and planted, of variable widths that run alongside rivers and streams and within the riparian zone. The riparian zone is a landscape

[2] UKCP18 are the UK Climate Projections produced by the Met Office. More information: UK Climate Projections (UKCP) - Met Office

unit that is open to fluxes to and from river systems and uplands driven by natural and social processes (CONVERGES definition, Dufour & Rodriguez-Gonzalez, 2019). The land alongside fluvial systems influences and is influenced by river processes (Dufour & Rodriguez-Gonzalez, 2019) such as nutrient and carbon cycling and regulating water flows.

River woodlands include woodland types which influence and are influenced by such processes and thus include the following types:

Riparian woodland: woodlands found on the bank of a natural body of freshwater especially a stream or river but can also include lochs (Parrott & MacKenzie, 2000). This zone on the bank is usually relatively narrow, often extending less than five metres on either side of watercourses and typically comprises native broadleaved woodland that is often unmanaged (Ngai e*t al.*, 2017). In the past, conifer plantations extended into these zones but now there is a programme of clearance to restore them to native woodland. When considering functional riparian woodland, the width of the zone will depend on the function and biogeochemical conditions of the site; geomorphology of watercourse (width, depth, flows, sediment), soils, geology and slope.

Floodplain woodland: all woodland lying within the fluvial floodplain that is subject to a regular or natural flooding regime (Ngai *et al.*, 2017). It typically comprises broadleaved woodland and can range from productive woodland on drier parts to unmanaged, native wet woodland in wetter areas. In Britain, natural floodplain woodland that originally covered most floodplains has been mostly cleared and the land drained for agriculture and urban development. Extensive remnants of natural floodplain woodland survive in just a few locations in in the UK (Kerr & Nisbet, 1996). Floodplain alluvial woodlands have high ecological and conservational importance; Scotland has ten Special Area of Conservation (SAC) where “alluvial forest with alder and ash” habitat is the main qualifying habitat feature of the site. This includes the Conon Islands, Lower River Spey-Spey Bay, Mount Alderwoods and Urquhart Bay Wood in the Highlands and Islands region, and the Shingle Islands in Eastern Scotland[3].

Gorge woodland: native trees in gorges where the influence of the riparian zone extends beyond the floodplain due to high humidity levels (MacKenzie, 1996). These woodlands have high conservation value due to limited disturbance from human activity e.g. *Tilio-Acerion* ravine forests which are found on steep, flushed slopes with open seepages and base-rich soils in gorge sites across Scotland are features of Special Areas of Conservation. This includes tributary streams of the River Tweed and Clyde Valley Woods in southern Scotland, which represents the most extensive complex of woodland gorges with *Tilio-Acerion* forests in Scotland[4]. Other gorge woodlands are designated Sites of Special Scientific Interest due to specialist invertebrate communities e.g. Ayr Gorge Woodlands. Oceanic riparian ravines associated with temperate rainforest on the west coast of Scotland are especially important for rare mosses and liverworts[5]. Gorge woodlands are usually remnants of ancient woodlands that cannot be easily re-created. Their distribution is constrained by topography which may provide shading to the river channel additional to the shading provided by trees. They provide core sites of high biodiversity to extend through riparian woodland creation.

Man-made riparian woodland buffers: Riparian woodland buffer zones occur on farms as areas between natural and artificial water courses, such as streams or ditches, and agricultural land. They

[3] More information on alluvial forest can be found here: Alder woodland on floodplains (Alluvial forests with Alnus glutinosa and Fraxinus excelsior (Alno-Padion, Alnion incanae, Salicion albae)) - Special Areas of Conservation (jncc.gov.uk)
[4] Further information available: Mixed woodland on base-rich soils associated with rocky slopes (Tilio-Acerion forests of slopes, screes and ravines) - Special Areas of Conservation (jncc.gov.uk)
[5] More information about mosses and liverworts associated with oceanic ravines can be found here Mosses and liverworts | NatureScot

are designed to intercept pollutants from runoff from the adjacent field. In addition to woodland, they can include grassland and wetland elements, these are called an Integrated Buffer Zones. When considering the design of riparian woodland buffers, the width of the buffer will depend on the function and biogeochemical conditions of the site, width of watercourse, soils, geology and slope.

Large woody material: the fallen stems, logs, sticks, branches, and other wood that falls into streams and rivers. All the river woodland types provide a source of large woody material (LWM). It can also include man-made large wood structures sometimes called artificial leaky dams. The term large woody material is also known as large woody debris (LWD) in the literature.

Definitions of the riparian zone and riparian ecosystem are as follows:

Riparian zone: the interface between the terrestrial environment and the freshwater habitat, including the land between the riverbank and the lower edge of upland areas not affected by river processes (McKenzie, 1996). An encompassing definition of river woodlands within a wider riparian zone has been adopted in this report to take into consideration that functional processes within the waters of stream-river networks are closely interlinked to land and such influences can extend beyond the local riverbank to wider scales. This embraces a landscape approach for rivers, or a 'riverscape approach' (Schumutz & Sendzimir, 2018), and a functional approach with the consideration of river processes.

Riparian ecosystem: Riparian ecosystems are not tied to a specific distance from the water's edge but rather to changes in vegetation type, soil type and moisture availability, and other ecological characteristics. They encompass the functional zones of influence of the river: lateral, longitudinal, vertical and temporal[6] (Figures 1-3).

- The longitudinal influence extends the length of the stream.
- The lateral influence begins in the water body and extends through the riparian vegetation, into the upland forest or dry land vegetation, to the point where overland flow (runoff) is initiated (see Figures 2 & 3)
- The vertical influence extends below the dry season water table and through the canopy of mature vegetation.
- Temporal influences are changes to the riparian ecosystem over time.

They include different river woodland types and other habitats such as wetland, which provide the structure for the system. Structural and functional characteristics combine to create ecological integrity for the riparian landscape. If the structure or function is compromised, the consequences will be apparent in the degradation of the area.

Figure 1: Identifying the riparian ecosystem (not to scale). Credit US Forest Service.

[6] For more information on US Forest Service definition 0423-1201-SDTDC: Riparian Restoration, Page 4 (fs.fed.us)

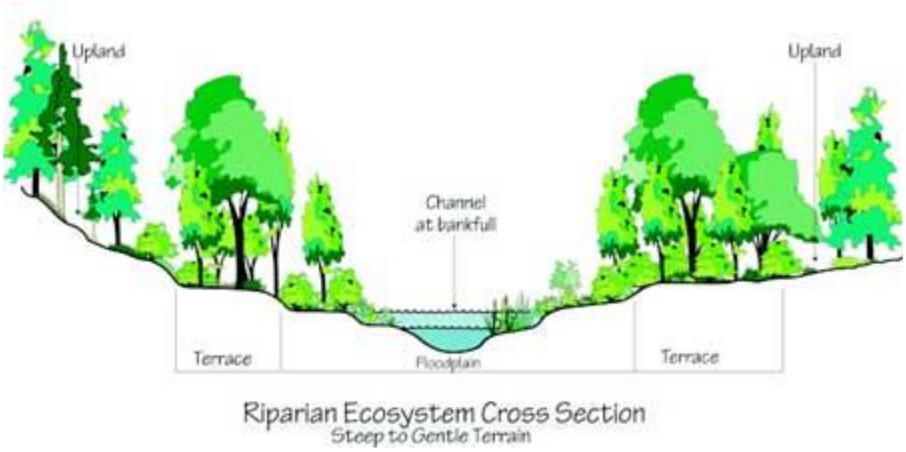

Figure 2: Riparian ecosystem cross section, steep to gentle terrain (not to scale). Credit US Forest Service.

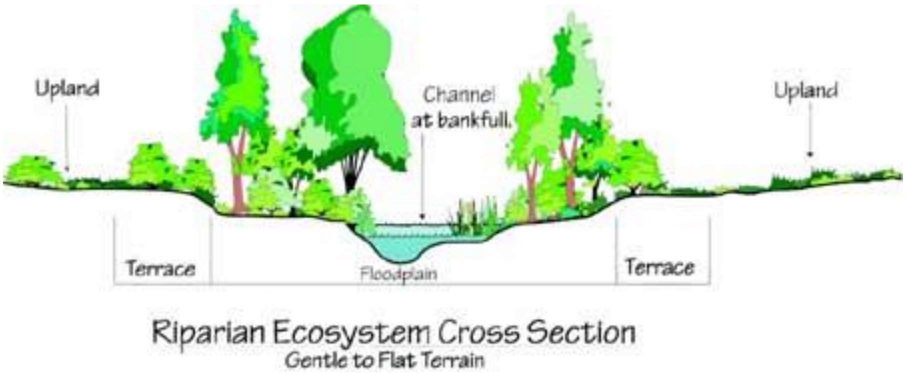

Figure 3: Riparian ecosystem cross section, gentle to flat terrain (not to scale). Credit US Forest Service.

1.4 Scope of review

The aim of the review is to provide a broad indication of the most up-to-date scientific evidence underpinning the environmental benefits that river woodlands provide. It is not a systematic review.

The river woodland types included in this evidence review include native riparian woodlands, flood plain woodlands, man-made riparian woodland buffers, natural and made-made large wood structures. Gorge woodlands are primarily considered in relation to their high value for biodiversity. Wider catchment-based woodlands in urban and rural areas can provide similar benefits to those identified in the review and some evidence in relation to woodland more generally is presented where specific evidence was not available.

The approach adopted to collect evidence seeks to identify and understand the pathways and biophysical processes that affect the provision of final goods and services (or benefits to people) and acknowledges that economic value comes directly from the consumption of these final goods and services (Binner *et al.*, 2017). Searches have been carried out for empirical evidence, not only to link biophysical processes with river woodlands but also for evidence which links river woodland measures with actual impacts, such as slowing flood flows or reducing sediment loads in waterways. This evidence can then be used in combination with decision support tools and valuation estimates to bring together a wider state of knowledge (Binner *et al.*, 2017).

Initially, the Riverwoods Technical Group was asked to provide evidence through semi-structured interviews on key evidence of which they were aware. As data was collected in a database for each benefit, further literature searches were undertaken, and evidence was followed up with individual scientists for clarification. The type of data asked and searched for, for the evidence report included:

- The most recent up-to-date comprehensive reviews (systematic and conventional reviews) and studies including quantified data on the benefits of river wood types
- Scottish studies. If this was not available, UK and international studies of relevance to Scotland, Scottish climatic and biophysical conditions.
- Evidence of biophysical processes underpinning the benefits and where this is supported by the science.
- Evidence of the relative magnitude of the effect in terms of its relative significance.
- Evidence of other factors influencing the effectiveness of measures such as location, scale, design and management.
- Evidence from consensus judgement from science experts providing a confidence rating on the potential effectiveness of measures.

Although some information was gathered on decision support tools and design and management guidance, it was not the focus of the report. Annex 2 provides an overview of available guidance and tools. Further work is required to review the most up to date decision support tools and guidance along with valuation estimates. A cost-benefit analysis of Riverwoods will form part of the business case with tailored evidence for individual sectors as part of further work and is not included in this report.

Evidence for benefits of river woodlands has been classified into four categories of: weak, moderate, strong and very strong evidence. This classification is based on the Level of Evidence Hierarchy pyramid ranking produced by Mupepele *et al.*, (2016) and incorporates the strength of modelling evidence (as illustrated and described in Burton *et al.*, 2018). It provides a level of confidence in the evidence based on the quality and number of studies. Where evidence is context- or scale-specific, this is stated clearly. Experts were used to classify the evidence using the criteria below. Strength of evidence of the biophysical processes underpinning the functions working was considered as well as strength of evidence linking woodland measures with actual impacts (and outcomes).

Very strong evidence	Systematic and conventional reviews based on robust empirical evidence. Projections made using well-established models that are based on the available physical principles, biophysical processes and utilise data from robust empirical evidence gathered in a wide range of settings	
Strong evidence	Studies with a reference/control. Before-After-Control-Impact (BACI) designs or multiple lines of moderate evidence. Projections made using well-established models which are based on the available physical principles, incorporate biophysical processes and utilise data from robust empirical evidence	
Moderate evidence	Observation studies based on studies with statistical testing OR descriptive studies without statistical testing. Projections made from models with some data input to determine parameters.	
Weak evidence	Studies without underlying data. Projections from models which represent theories without underlying data.	

The benefits to people have been defined with reference to globally adopted frameworks. The users of the evidence in this report are likely to include a range of sectors: financial investors, businesses, land and river managers, Scottish Government and its agencies. The benefits are defined using the language in the UN Sustainable Development Goals which have been globally adopted by governments and businesses. Benefits include: clean water, climate action for drought and flooding mitigation, carbon sequestration, clean air, sustainable soils, biodiversity conservation, good health, wild fish and angling, and sustainable food and energy production.

The benefits are ordered according to the sections in Common International Classification for Ecosystem Services (CICES v5.1), which has been widely adopted in Scotland and across Europe. Regulation and maintenance services are shown first, followed by cultural services and provisioning services. Evidence is presented under different functions which help deliver each benefit.

2 Healthy and resilient river systems

2.1 What is a healthy and resilient river system?

The goal of the Riverwoods initiative is to create a network of river woodlands supporting healthy and resilient river systems across the whole of Scotland. This section interprets the main factors used to define healthy and resilient river systems.

2.1.1 Healthy river system

The characteristics of healthy rivers are:

1. Controlled by natural morphological processes;
2. Dominated by natural structure in channel and floodplain;
3. Formed by interconnected water and sediment flow, both in channel and floodplain;
4. Thermally moderated through a mix of light conditions and depths;
5. Unpolluted;
6. Oxygenated;
7. Support rich animal and plant-life.

River woodlands influence the condition of rivers and streams by influencing physical, chemical and biological processes within the riparian ecosystem. The flows of energy, materials and organisms are interwoven in complex, cross-linked relationships of ecosystem functioning (Schumutz & Sendzimir, 2018)

Native riparian and floodplain woodlands have an essential role in carbon and nutrient cycling linking land to water and water to land, and recycling nutrients and carbon from source to sea (MacKenzie, 1996; Schumutz & Sendzimir, 2018). Native riparian forests control the flux of nutrients from terrestrial to aquatic ecosystems. In-stream nutrients are transported downstream in a process called nutrient spiralling (MacKenzie, 1996). However, it is not just a one-way flow of nutrients. The riparian zone retains nutrients during their displacement downstream which can then be returned to land. A flooding river can leave behind substantial amounts of sediments and nutrients in the floodplain (Walling, 1999) representing a large nutrient subsidy to terrestrial systems. The food web stretches between the freshwater and land transition zone (Petersen *et al.*, 2004; Thomas *et al.*, 2016) and enables the flow of nutrients and carbon in both directions as animals live, feed and die in both environments. As well as carbon and nutrient recycling, river woodlands play a role in regulating the flow of water.

2.1.2 Resilient river system

Ecosystem resilience is the inherent ability to absorb various disturbances and reorganise while undergoing state changes to maintain critical functions (Sasaki *et al.*, 2015). This means that a resilient ecosystem is one that can freely adjust to accommodate an environmental change (Addy *et al.*, 2016) such as climate change. River resilience is enhanced by maintaining natural physical processes. This includes connectivity between upstream and downstream reaches and between rivers and their floodplains, to allow free movement of water, sediment, organic matter and living organisms. By restoring river woodlands, resilience is enhanced through adjusting natural geomorphological processes (erosion, deposition, channel adjustment), dissipating energy of high flows, maintaining the connectivity of biological communities, and by increasing shading of the water, reducing the risk to species sensitive to rising water temperatures.

2.1.3 Healthy rivers in modified landscapes

In a modified landscape, where there are constraints from other activities and uses, the focus is to restore natural processes as much as possible. River wood types that have been included in this report include those modified to provide particular functions e.g., to manage diffuse pollution, or address flood risk. Whilst the "ideal" vegetation for the riparian zone is dynamic natural vegetation including trees and shrubs similar to the watercourses of an ancient forest landscape, this is constrained in our modified landscapes. River woodlands can be designed and structured to deliver specific functional roles in riparian ecosystems.

2.2 How do we measure and monitor the condition of river woodlands and healthy and resilient river systems?

2.2.1 Current approach

Under the European Water Framework Directive (Directive 2000/60/EC), which has become law in Scotland as the Water Environment and Water Services (Scotland) Act 2003 (WEWS Act), the status of Scotland's water environment is classified using environmental standards to determine the ecological quality of freshwater ecosystems and for the delivery and protection of good water quality.

A general requirement for ecological protection, and a general minimum chemical standard, was introduced to cover all surface waters. These are the two elements "good ecological status" and "good chemical status". Good ecological status is defined in the Water Framework Directive (WFD), in terms of the quality of the biological community, the hydromorphological elements, and the chemical and physio-chemical characteristics. The main aim of WFD is to achieve good ecological status which requires healthy and resilient river ecosystems.

In Scotland, the environmental standards incorporate biological, chemical, hydrological and morphological components of the aquatic ecosystem. For example, environmental standards for biological conditions include composition of aquatic flora and freshwater invertebrates. Environmental standards for morphological condition include assessment of bed, banks and riparian vegetation of rivers. Where trees are appropriate to the location, an assessment of density and structure of natural woody vegetation is considered to represent the best riparian vegetation for protecting morphological status (Greig *et al.*, 2006).

In Scotland, MImAS (Morphological Impact Assessment System) (Greig *et al.*, 2006), is the tool created to classify morphological condition in baseline rivers. The classification provided by MImAS is based on river type, morphological pressures and riparian vegetation. Therefore, information related to riparian woodland can be extracted and analysed to assess the condition of the riparian vegetation in Scotland in terms of density (Figure 4) and structure (Figure 5) but not composition or species richness. Although, MImAS only considers the presence of riparian vegetation within the first two metres from the bank top, new developments in MImAS-2 are considering including a wider extent of the riparian vegetation more in line with the principles of Riverwoods.

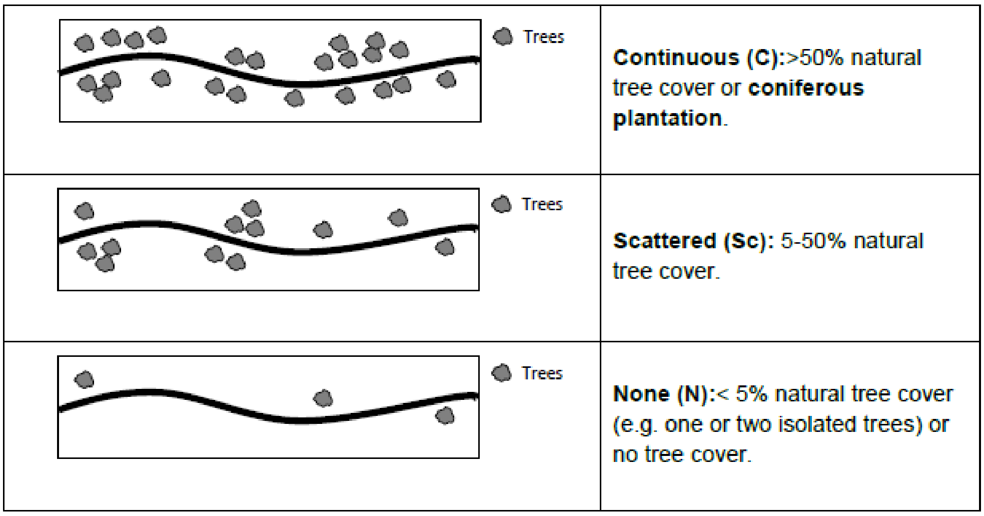

Figure 4: Density categories used in riparian vegetation surveys

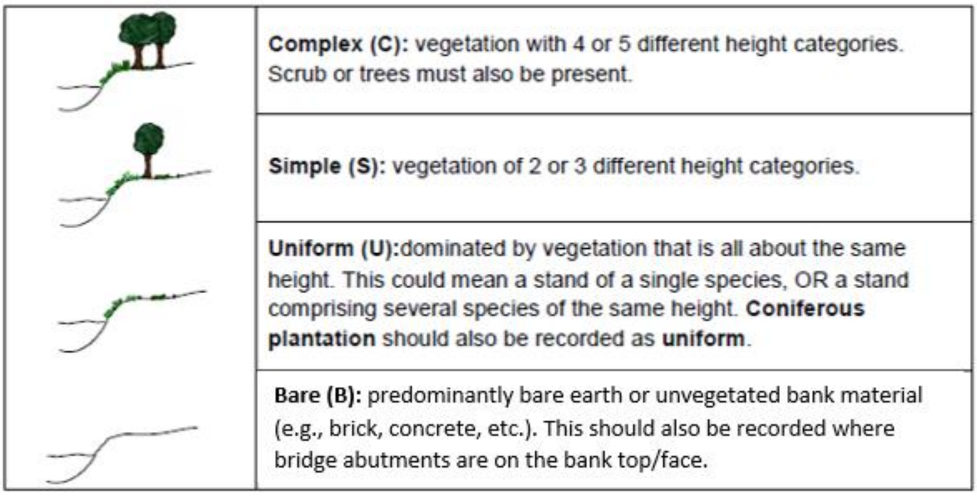

Figure 5: Structure categories used in riparian vegetation survey categories

The two metres width limit is too narrow in many cases to include functional areas within the riparian zone that supports a healthy river system and provides benefits to people. However, the information provided by MImAS is still useful to identify priorities and a programme of actions for restoration of river woodlands.

Figure 6 shows a map of the quality of riparian vegetation in Scotland based on density and structure extracted from MImAS. The map shows baseline river water bodies, and the data was extracted from field surveys for less than good water bodies and remote sensing for the water bodies at good or high condition. The description of different quality classes is in box 2. Riparian woodland habitats in poor condition lack tree cover and consist of either bare ground or uniform vegetation such as grass and plantation. Riparian woodland habitats in good condition consist of trees with continuous or scattered density and complex structure. For these reaches at good riparian vegetation condition status, further field checks are required to assess if they are the right native species. For these checks, biogeographical studies of riparian vegetation are required in Scotland. Tree planting would involve native species which are genetically and phenotypically suited to the site and of high quality based on legislation in the EU Directive 1999/105/CE on the marketing of forest reproductive material.

These analyses of different quality categories of riparian vegetation can be used at a national scale to allow strategic planning of river wood restoration rather than relying on opportunistic restoration.

Box 2: Classes of riparian vegetation referenced in figure 6.

- **Good:** This includes margins classified as 'complex - continuous' and 'complex - scattered'.
- **Moderate:** This includes 'simple - continuous' and 'simple - scattered'.
- **Poor:** This includes either 'bare or coniferous plantation - none', 'bridge', 'gap', 'multi surface (garden)', 'simple - none' and 'uniform - none' and 'uniform-continuous'
- **Other habitats:** This includes wetland vegetation types including 'heath – high altitude', 'wetland', 'wet woodland', 'wet grassland', 'springs, flushes and seepages', 'fen', 'swamp', 'reedbed', 'wet heath', 'peat bog', 'saltmarsh', 'dune slacks' and 'machair'. This also includes 'open water'. More work is required in these habitats to assess good condition and conservation value in their own right and therefore not suitable for riparian woodland restoration.

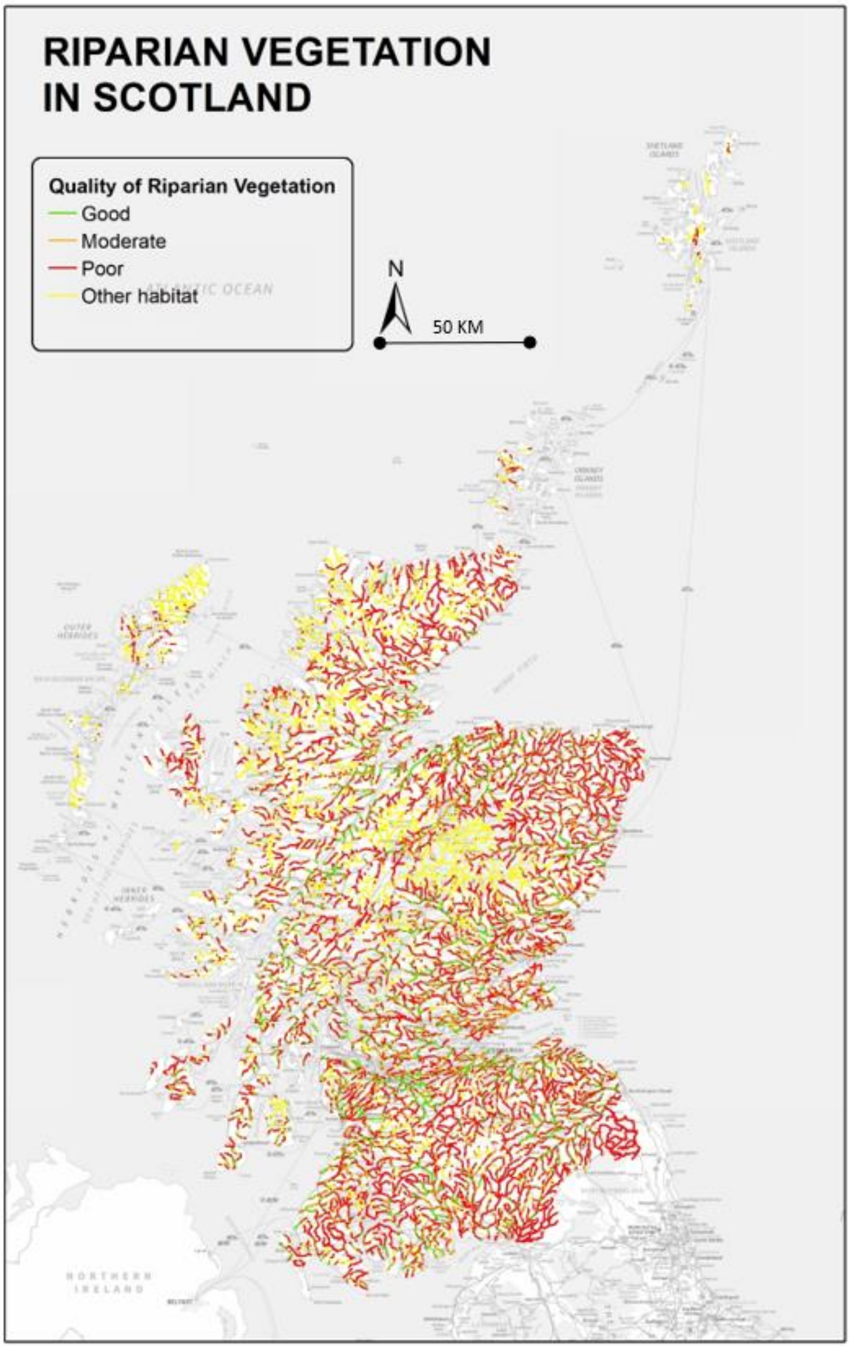

Figure 6: Riparian vegetation quality in Scotland based on MImAS for baseline water bodies. The survey for less than good water bodies was completed in 2015-16. See Box 2 for description of classes.

2.2.2 Approach under development

COST Action Converges (CONVERGES, Knowledge Conversion for Enhancing Management of European Riparian Ecosystems and Services) was created in 2017 to influence WFD and incorporate the findings of the importance of riparian woodlands as a part of healthy water bodies. The Converges project has developed some material to better assess ecological condition of riparian vegetation for Water Framework Directive purposes and some principles to integrate riparian vegetation in national policy (Urbanič *et al.* 2022).

Using the current WFD approach to assess the quality of riparian vegetation status requires comparison of the current conditions to a previously established reference condition, which can be challenging to define. The reference conditions for riparian vegetation would need to:

- Account for the natural vegetation dynamism following relevant floods,
- Consider species succession according to channel evolution at different temporal scales,
- Evaluate the potential dynamic equilibrium over the long term.

CONVERGES working groups have been discussing different ways to make use of the riparian vegetation. A different approach could be to evaluate the riparian ecosystem with respect to its naturalness/functionality vs. artificiality (González del Tánago *et al.*, 2021). This involves distinguishing vegetation attributes that related to:

- Naturalness of a riparian system (reflecting no or little alteration by human influence)
- Healthy functionality (free fluvial processes e.g.: channel mobility, natural regeneration)
- Artificiality (reflecting human pressures that induce changes in riparian vegetation structure).

2.3 Limitations & Gaps in Research

A national map of riparian woodland cover and a riparian woodland potential map similar to that produced by the Environment Agency would be useful for Scotland [7]. The riparian woodland potential can be linked to maps of native riparian woodland including tree species for different regions and catchments. These maps are required not only for classification purposes but to support national efforts for the restoration of healthy riparian corridors in Scotland.

Biogeographical studies that provide information about spatial distribution patterns of species at the catchment scale (Ricklefs & Jenkins, 2011), along with studies of broad plant functional traits, could be used to identify theoretical "undisturbed" vegetation types, riparian plant formations and associations along the river corridor at the regional scale. The biogeographical studies for riparian vegetation in Scotland will help to inform reference condition work.

Further work is needed to validate vegetation indicators and establish their metrics and relative weights. New versions of MImAS in SEPA need to integrate most up-to-date scientific knowledge on riparian vegetation with morphological classification.

[7] WWNP Riparian Woodland Potential - data.gov.uk

3 Assessment of benefits for people

3.1 Clean water

3.1.1 Overview of benefit

This benefit focusses on how river woodlands help manage pressures on the environment that adversely affect the quality of freshwater. In 2019, 13% of water bodies in Scotland were worse than good condition due to water quality[8]. Rural diffuse pollution is the main pressure on water quality in Scotland's waterbodies, largely due to agriculture and forestry in rural areas. Soil erosion and run-off results in suspended sediments, nutrient pollution and toxins from pesticides entering neighbouring water bodies and impairment of water quality.

This pressure on Scotland's water resources is predicted to increase with climate change. Higher intensity rainfall events and flooding are increasing erosion and suspended sediment in runoff from bare soils. Whilst lower summer flows are reducing dilution capacity of the river making pollutants more concentrated[9] . Climate change models predict that low flows and higher temperatures will also increase rates of chemical exchange in the riverbed with a shift from present day low to moderate dissolved nutrient (oligotrophic/mesotrophic) conditions in UK rivers to a moderate to high dissolved nutrient (mesotrophic/eutrophic) system by 2080 (Hutchins *et al.*, 2010).

Riparian woodland buffers have the potential to contribute to safeguarding clean water by controlling diffuse pollution from the land and reducing pollutants in our waterways. River woodlands can also provide shade that regulates pollution interactions with light and temperature, such as controlling excessive algae in rivers triggered by an excess of nutrients from the land. The risk of algae blooms (benthic/periphytic) in rivers in Scotland may increase if rivers become slower flowing, warmer and sluggish, and dead zones may appear more frequently with climate change.

This section focuses on presenting the evidence underpinning the role that riparian woodland buffers play in mitigating diffuse pollution under four main functional categories: capturing nutrient pollution, capturing sediments and stabilising banks, capturing pesticides and herbicides, and capturing pathogens. This section also includes evidence of the role that river woodlands play in controlling algae blooms in waters enriched by nutrients from diffuse pollution. Evidence for the biophysical processes underpinning the functions is presented first followed by quantified evidence of measured effects. Ratings of the relative effectiveness of measures has also been included in this section as undertaken in previous review work by Stutter *et al.*, (2020).

Beneficiaries

Many industries require clean water as a resource for production, such as food and drink manufacturing, milk production, freshwater fisheries, and agricultural production. Everyone requires clean drinking water as a basic need, provided by Scottish Water and private water supplies. Individual householders/businesses or a community with a shared communal supply will be interested in maintaining their private water supply. People also need clean water for recreational uses such as wild swimming and other water sports. Woodlands generate water quality improvements which, in turn, benefit water companies through reductions in the treatment costs associated with the production of drinking water. Water bill payers can hence benefit from reduced treatment costs. Scottish Water has a responsibility to reduce the impacts of sewage discharges. The prevention of sediment runoff from the physical buffer created by riparian woodland may be beneficial to reservoir operators with costs saved from less dredging and less sediment flushing from reservoirs.

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[8] RBMP 3rd Cycle (sepa.org.uk) Informatics Hub
[9] Adaptation Indicators (climatexchange.org.uk)

3.1.2 Evidence for integrated control of diffuse pollution

An overview of the role of riparian woodland buffers in providing integrated control of diffuse pollution from different sources is provided here followed by sub-sections consider specific pollutants sources in more detail.

There is a growing body of research which shows that riparian woodland buffers can protect water quality by mitigating diffuse pollution from agriculture. The empirical evidence has been summarised well in reviews such as Forest Research's monograph Woodland for Water publication (Nisbet *et al.*, 2011). The European Cooperation in Science & Technology (COST Action: 15206) Short Term Scientific Mission report updates this evidence base summarising current understanding of the effectiveness of riparian woodland buffer creation measures for reducing key diffuse pollutants based on site-based experiments in Europe and North America (Silos, 2017). Reviews of evidence for the effectiveness of buffer strips have also been undertaken by Stutter *et al.*, (2019, 2020, 2021), which included forested buffers.

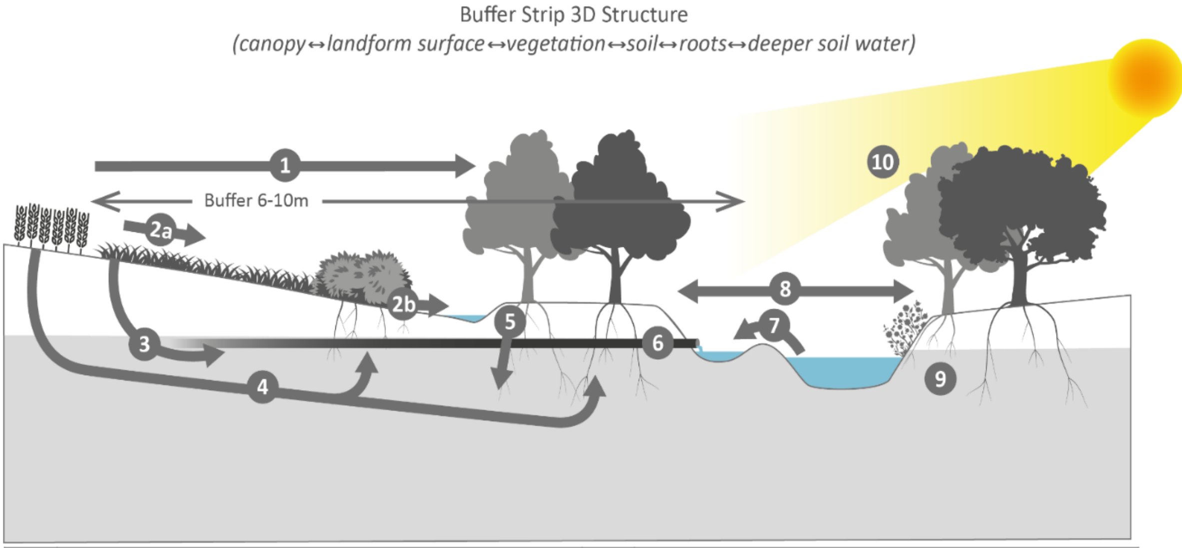
There is also evidence that floodplain woodland plays a role in reducing diffuse pollution by enhancing siltation and sediment retention, nutrient removal (phosphorus and nitrogen) and fixing heavy metals (Ngai *et al.*, 2017). However, floodplain woodlands, natural or restored, often include wetland habitats of highest value when not nutrient enriched. It is therefore important for river managers to consider the potential detrimental consequences of using floodplain woodlands for nutrient mitigation (Schumutz & Sendzimir, 2018). The reconnection and establishment of floodplain woodlands and wetlands on former agricultural land, vacant urban or derelict land needs to consider the nutrient and metal legacies in the soils first.

Functional processes

Stutter *et al.* (2020) describes how vegetation including trees functions within riparian buffers. The hydraulic roughness of ground vegetation, tree stems, deadwood, and surface rooting slows and/or temporarily stores surface run-off, reducing carrying capacities of particles and associated pollutants. Rooting, especially by trees, creates larger soil pores, increasing infiltration capacity and the retention of dissolved nutrients at depth. Growth of biomass increases nutrient uptake and removal. Leaves, dead wood and decaying roots increase soil organic matter, driving microbial assimilation or breakdown of chemicals. The physical barrier created by tall vegetation reduces pesticide spray drift and helps remove pollutant gases such as ammonia (See Figure 7).

Measured effect

Stutter *et al.*, (2021) give a synthesis of studies analysing site-specific factors which influence managed riparian buffer effectiveness across pollutants. Tree planting into riparian buffers zones was found overall to have positive effects, with limited negative study effects, depending on factors of landscape position and buffer design. However short duration studies of riparian woodland found no significant effects, potentially as benefits had not yet been realised. As a result, inclusion of trees (relative to grass buffers) was taken as having strong evidence through agreement and number of studies for positive effects on the pollutants, sediment, total phosphorus, dissolved phosphorus, total nitrogen, ammonium, and pesticides in terms of retention in riparian zones and stream protection. In longer term studies in the US multi zone riparian buffers can reach maximum efficiency for sediment removal in as little as five years and nutrient removal in as little as 10–15 years (Schultz *et al.*, 2003). See sections 3.1.3 to 3.1.5 for quantified information on measured effects for nutrients, sediment, pesticides and herbicides.



1	Reduced airborne spray drift of agrochemicals due to interception by tree canopy	6	Stopping direct discharges from soil drains to watercourses allows time for pollution removal
2	Filtering pollutants in runoff by trapping particles amongst vegetation (2a) and by water retention in hollows created by resculptured ground profiles (2b).	7	Altered bank profiles promote rewetting, water retention and sediment trapping
3	Improved infiltration and delayed vertical drainage promotes natural processing of nutrients and other contaminants by soil microbes and plants	8	Growth of riparian and aquatic vegetation increases channel 'roughness' and leaf litter inputs, aiding processing and removal of pollutants
4	Nutrient uptake and utilisation by growing vegetation	9	Tree rooting stabilises banks reducing erosion and sediment input
5	Enhanced levels of soil organic matter aids natural attenuating processes in soils	10	Increased shading cools water temperature and reduces thermal stress to aquatic life

Figure 7: 3D Buffer strips (Stutter *et al*., 2020)

Factors influencing effectiveness

Including trees as part of riparian buffers is beneficial for the control of diffuse pollution, although the effectiveness of such measures depends on several variables including woodland design and management, location and scale. Researchers working with policy and practitioners have called for a conceptual rethink of the structural elements of riparian buffer zones focusing on using engineering principles to recreate natural processes in buffers, many of which can be associated with wooded landscape elements, and to apply these within intensely farmed landscapes (Stutter *et al*., 2019). These elements have been developed in the UK into the 3D buffer zone concept seeking to maximise below and above the ground processes to tackle pollution pathways from deeper soil waters, artificial drainage, surface run-off and the air (see Figure 7, Stutter *et al*., 2020).

An ideal 3D buffer design includes deep roots, enhanced soil biogeochemical processing, run-off capture by re-sculptured ground surface and canopy interception. An integrated buffer zone (IBZ) is a design packaging many of these elements. Examples have been built and tested at field sites across Northwestern Europe including at Balruddery in Aberdeenshire, Scotland with positive results for reducing total nitrogen and phosphorus transport by surface and subsurface pathways to small streams and rivers (Zak *et al*., 2019). One element of the IBZ design is a tree belt, adjacent to a linear wetland, so tree biomass can uptake nutrients after the passage of runoff at the field edge is slowed. Although the IBZ design is specific to tackling diffuse pollution on intensive cropland situations, elements may be applied to wider riparian woodland situations. For example, elements such the trees intercepting air pollutants, and stabilising banks alongside wetlands processing nutrients and intercepting subsurface pathways may be applied to address specific issues as part of the 3D buffer concept in urban and rural areas (Stutter *et al.*, 2020).

3.1.3 Controlling nutrient pollution (phosphorus and nitrogen)

Functional processes

The main biophysical processes which underpin the function of riparian buffers to control nutrient pollution with study results showing positive influences include physical trapping by infiltration, microbial processing and plant uptake (Stutter *et al.*, 2020).

Measured effect

The majority of studies that measure the effects of retaining nutrient pollution by active tree planting and management in riparian buffer zones show consistent positive effects for the retention of total phosphorus, dissolved phosphorus, total nitrogen and ammonium (Stutter *et al.*, 2021). The weight of evidence (number of studies) has been classified as strong (n = 5 to 10) for these pollutant types in the Stutter *et al.*, (2021) review.

Empirical data from site-based experiments in North America and Europe found that for nitrogen, the effectiveness of woodland buffers to reduce nitrogen in surface run-off was very positive (>70% reduction in nitrate nitrogen concentrations (NO_3-N (mg/l)) achieved in all studies), across a range of climates and types of forest (hillside woodland, riparian woodland and shrub) (Silos, 2017). For oceanic riparian woodland, there was a 74% average reduction in nitrate nitrogen concentration in surface run-off and a highly positive relationship between buffer width and effectiveness. Natural riparian woodland (native to the area) appeared to be more effective at reducing nitrate nitrogen compared to planted riparian woodland buffers (planting of native or non-native tree species). Restored woodland buffers (planted area under a restoration project or semi-natural plantation) were the least effective, probably due to the lower maturity/age of these treatment systems but these trials also had low sample sizes (n=6). Results for concentration of phosphorus (mg/l) in surface run-off indicated that riparian woodland buffers are less effective at reducing phosphorus compared to nitrogen (Silos, 2017). Average reductions in concentrations of phosphorus of nearly 40% were found for oceanic climates compared to 16% for continental zones. There was a positive relationship between effectiveness and buffer width, while planted riparian buffers appeared to be more reliable for reducing phosphorus in runoff compared to natural riparian woodland or restored woodland buffers.

A study of integrated buffers (250 - 800 m^2), designed to intercept tiled drainage using linear ponds and wet woodlands were found to be effective at removing nitrogen by 23 - 37%, total phosphorous by 18 - 52%, and to increase sediment retention by 0.5 - 1.3 kg m^{-2} compared with input amounts (Zak *et al.*, 2019). Schultz *et al.*, (1995) measured the effect of a multi species buffer strip consisting of a 20 metre wide filter strip consisting of four or five rows of fast-growing trees planted closest to the stream, then two shrub rows, and finally a seven m wide strip of switchgrass established next to the agricultural fields. An integral part of this system was streambank stabilization using willow bioengineering and a constructed wetland to intercept nitrogen, phosphorus and sediment pollutants in field drainage tile water flow. They found that buffer areas reduced nitrate nitrogen concentrations by more than 80% between adjacent fields and a stream in Central Iowa compared with control plots (12 to 2 mg NO3-N l^{-1}) (in Nisbet *et al.*, 2011). A review of the longer-term plot study in this catchment found that a seven metre wide native-grass filter can reduce sediment loss by more than 95%, and total nitrogen and phosphorus in the surface runoff by more than 60%. Adding a nine metre-wide woody-buffer results in removal of 97% of the sediment and 80% of the nutrients. There also is a 20% increase in the removal of soluble nutrients with the added width. Water can infiltrate up to five times faster in restored six-year old buffers than in row cropped fields or heavily grazed pastures (Schultz *et al.,* 2003).

Modelling can help with understanding the interactions of different functional processes and therefore designing effective riparian buffers. For example, work by Zhang *et al.*, (2010) showed that buffers composed of trees had higher nitrogen and phosphorus removal efficacy than buffers composed of grasses or mixes of grasses or trees. The model integrated empirical data and included variables which influence efficiency such as buffer width, buffer slope, soil type and vegetation type.

However, there is a need to differentiate in modelling the difference between the lower outputs of nutrients that would be expected from modelled woodland compared with agricultural crop land use, and the role the woodland has in retaining nutrients. For example, Baksic (2018) reviews modelled evidence from the application of the Soil and Water Assessment Tool (SWAT)[10] comparing source areas in Europe to suggest that average nitrogen loads in deciduous and mixed forest areas (1.6 kg $ha^{-1}yr^{-1}$) are lower than in agricultural areas (e.g. corn: 22 kg $ha^{-1}yr^{-1}$; pasture: 4 kg $ha^{-1}yr^{-1}$) (Baksic, 2018). Average phosphorus loads in deciduous (0.12 kg $ha^{-1}yr^{-1}$) and mixed forest areas (0.14 kg $ha^{-1}yr^{-1}$) were also lower than in agricultural areas (e.g., corn 2.15 kg $ha^{-1}yr^{-1}$; pasture 0.61 kg $ha^{-1}yr^{-1}$). Baksic (2018) points out the need for models that understand the interaction between different land uses in intercepting the transport of pollutants to water. This includes the role of riparian woodlands in intercepting pollutants from upslope agricultural land use.

Factors influencing effectiveness

The effectiveness of riparian woodland buffer strips for nutrient uptake and retention depends on design, management and site factors. Empirical studies have demonstrated variable results linked to differences in previous land use history, depth of water table and soil type (Nisbet *et al.*, 2011).

Some studies have found woodland buffers to be more effective at removing nutrients than grassland whilst others have shown the opposite to be the case (Nisbet *et al.*, 2011). Feld *et al.*, (2018) describes how a buffer width of 30 m was reported to effectively retain nitrogen and phosphorus from surface and sub-surface groundwater runoff if buffers consisted of multiple zones of mature wooded vegetation and grass strips. The comparative ability of vegetation to remove nitrate from groundwater is likely to differ between species. For example, nitrogen-fixers such as Red Alder could be expected to increase nitrate concentrations, while more productive species like some willow and poplar hybrids would enhance nutrient uptake.

Older, unmanaged riparian woodland is likely to have a lower nitrogen uptake than younger, managed stands (Nisbet *et al.*, 2011) due to trees and shrubs with deep and dense root systems retaining nitrogen more effectively at intermediate stages of growth (~15 years) than mature stages (~40 years; Feld *et al.*, 2018).

Trees must also be actively managed to maintain nutrient uptake in man-made riparian woodland buffer strips (Stutter *et al.*, 2020). Although thinning or harvesting trees could potentially damage soils and temporarily reduce pollutant trapping, impacts can be minimised by following good management practices and appropriate design such as by phasing or zoning harvesting work to always retain some standing trees. Planting fast growing tree species such as willow or alder and managing these for bioenergy as short rotation coppice (SRC) or short rotation forestry (SRF) can offer ways of maximising nutrient offtakes (see section 3.11 for more detailed information on provision of energy from SRC).

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[10] The SWAT model was identified as the preferred hydrological model of choice to study the response of hydrological systems to natural and anthropogenic pressures and for planning sustainable use of water resources in a global literature review of models (Baksic, 2018). It is highly used around the world in agricultural land management, with high accuracies when locally well calibrated. However, it is sensitive to management operations such as fertiliser inputs and care is required to ensure correct parameterization, including for parameters of vegetation growth that control nitrogen uptake.

Higher concentrations of soil organic matter in buffer strips can increase microbial activity. Although microbial activity may benefit pesticide degradation and denitrification processes in vegetated buffer strips, the effect on P retention may be negative through increased turnover and subsequent remobilization of particulate phosphate to a more soluble form. This can increase phosphorus loads in overland and subsurface flow. Some studies find an increase in dissolved phosphorus from vegetated buffers compared with adjacent land. For example, in a BACI study of a small catchment in Western Australia over ten years, dissolved reactive phosphorus to total phosphorus ratio changed from 0.5 attached to sediment prior to planting riparian buffer strips to 0.75 after the vegetated buffer strips had been in place for four years. However, in this study suspended sediment in the catchment dropped from over 100 kg $ha^{-1}yr^{-1}$ to less than 10 kg $ha^{-1}yr^{-1}$ following creation of the strips. Observations suggest that this was the result of reduced bank erosion and increased channel stability. Riparian management had limited impact on total phosphorus concentrations or loads but contributed to a change in phosphorus form (Section 3.1.4). (Robert *et al.*, 2012, McKergow *et al.*, 2003).

Studies have found highly variable buffer nitrate retention, from approximately 25% to near-complete (95%) retention for six metre buffer widths (Stutter *et al.*, 2020). This has been explained by the fact that in systems where nitrate is transferred to streams via deeper groundwater, gains in efficiency require larger buffer widths for greater root uptake. The design of buffers, thus need to take groundwater influences into account. Groundwater influences stream ecosystem structure and function and via influential variable source areas (VSA). VSA is the hydrological concept that runoff-generating areas in the landscape will vary in location and size over time. The VSAs are not static, they will increase and decrease in size and appear in various locations depending on time of year, rainfall, temperature, topology, and vegetation among other factors. The research found that where groundwater emerges in riparian zones and encounters organic top-soils, this results in heightened microbial processing and lower redox before entering the streams (Kuglerová *et al.*, 2014; Erdozain *et al.*, 2020). A range of approaches to defining the riparian zone have been developed derived from the Digital Elevation Model (DEM) and, increasingly, Light Detection and Ranging (LIDAR) data to examine relationships between VSAs and various water quality and biological variables (Kuglerová *et al.*, 2014; Erdozain *et al.*, 2020). Most hydrologically connected areas are more sensitive to disturbance and fixed width riparian buffer zones that fail to include the entire VSA can fall short of adequately protecting streams from management activity on the adjacent land. There remain weaknesses such as the difficulty in identifying spring flushes and seepages that are controlled by local geology.

3.1.4 Capturing sediment and stabilising riverbanks

Functional processes

The ability of riparian woodland buffers to intercept run-off and trap suspended sediment from run-off pathways involves physical trapping by deposition and infiltration (Stutter *et al.*, 2020). Riparian woodland buffers and native riparian woodlands can also reduce bank erosion and sediment loss to water ways by stabilising riverbanks with the strengthening action of their roots. This is supported by a wide range of evidence with empirical data predominately from the international literature (Hubble *et al.*, 2010; Rood *et al.*, 2014; Hughes, 2016).

Tree roots help aggregate soil particles increasing soil stability and reducing runoff and increasing water infiltration. This effect is due to tree root exudates that could explain approximately 20%–75% of the variation on the anti-erodibility of soils (AES) according to Wang *et al.* (2017). Below ground, their deep roots provide strength to the soil and improves its structure to benefit infiltration and water retention. Schultz *et al.*, (2003) found that the large woody roots from forest riparian buffers were often found extending 2 m to 3 m or more into the soil provide additional strength to stream bank.

Other researchers consider that mycorrhizal fungi provide the main binding role between soil particulates (see section 3.6 on soil health for further details).

The action of riparian and floodplain woodland in encouraging out-of-bank flows and slowing down flood flows promotes fine sediment deposition and retention, reducing downstream siltation (in Ngai *et al.*, 2017). Hughes (2003) reported that a high proportion of fine sediments deposited can lead to thick over-bank deposits amongst floodplain trees. These sediments under the trees retain moisture which encourages germination and regeneration of vegetation. The vegetation growth further stabilises the riverbanks. However, woodland is not essential as other types of vegetation and features can also slow flows and promote deposition. There is evidence from the Rhine that highest deposition rates were found where water velocity was reduced by vegetation structure (reedbeds) or by a drop in surface elevation (pond). Sediment deposition was not higher in woodlands than in grassland types (Olde Venterink *et al.,* 2006).

Measured effect

There are many studies which measure the effects of retaining sediment pollution by active tree planting management in riparian buffer zones (Stutter *et al.*, 2021). There is strong evidence amongst riparian management buffers for greater efficacy of fine sediment trapping with wooded relative to grass-only buffers with a substantial number of studies showing some non-significant, but overall positive effects dominating over negative effects at plot and field scales (as reviewed by Stutter *et al.*, 2021).

Empirical data from site-based experiments in Europe and North America found that for simulated rainfall treatments, riparian woodlands in the oceanic climate zone reduced suspended solids by 75%, on average, compared to the control measure of no buffer (Silos, 2017). The review compared results for natural, restored and planted riparian woodlands. It found results for the planted riparian woodland treatments were less variable compared with the natural and restored treatments. This implies that designed woodland measures were more consistently effective.

Sediment eroded from banks is often not a major source of sediment compared with sources direct from cultivated land, therefore ideally it is better to stop soil erosion in the fields. However, bank erosion can be a significant source, for example Walling *et al.* (2003) has studied the sediment budgets of sub-catchments of the Avon and Wye in SW England, where bank sources varied from 4 to 55% of total suspended sediment. In one study of interstitial fine sediment in samples retrieved from salmonid spawning gravels in the south-west of England, channel bank sources were responsible for as much as 84% of the total load (Walling *et al.* 2003).

In the UK, measurements generally show consistently lower soil losses from the bank and greater bank stability for watercourses lined by riparian woodland, compared to other land uses. For example, in the River Frome in Dorset, the weighted seasonal mean of contributions of fine sediment recovered from the channel bed sampling sites was lower for woodland than other land-use types including pasture and cultivated fields (Collins & Walling, 2007). Stream banks with riparian woodland buffers in a US catchment lose up to 80% less soil than row cropped or heavily grazed stream banks (Schultz *et al.*, 2003).

A study in Canada found that river channels lined with broadleaf trees were more effective than grasses at resisting bank erosion from major river floods (Rood *et al.*, 2014). Along a 23 km reach with alternating forest and grassland, 15 locations displayed substantial change as the river moved a channel width (45 m) or more with meander migration, or up to 200 m with channel avulsion. All ten locations with major change (>75 m) occurred where the floodplain zones were occupied by grasslands, sometimes with small shrubs. In contrast, channels flanked by forest were minimally altered (<15 m), and deciduous (black cottonwood, *Populus trichocarpa*) or mixed deciduous-coniferous groves were effective at resisting erosion.

There is some modelled evidence from the application of the Soil and Water Assessment Tool (SWAT) comparing source areas in continental Europe to suggest that average sediment export loads in deciduous forest (1 kg $ha^{-1}yr^{-1}$) and mixed forest areas (2 kg $ha^{-1}yr^{-1}$) are lower than in agricultural areas (e.g., corn 10.6 kg $ha^{-1}yr^{-1}$; pasture 3.3 kg $ha^{-1}yr^{-1}$) (Baksic, 2018*).* There is modelling evidence to show that the establishment of woodland in the uplands along run-off/sediment pathways can interrupt and reduce the transport of sediment to watercourses. In a single study in the Upper Wharfe catchment in the Yorkshire Dales National Park, modelling work (using SEDMAP with a root cohesion parameter) has shown an 80% reduction in coarse sediment loading from strategically planting 5.2% of the catchment in areas of high risk of slope failure and along source flow pathways (Lane *et al.*, 2008). The results indicate that it is possible to achieve significant reductions in sediment yield through source control using woodland measures.

Factors influencing effectiveness

Soils, slope, buffer width and understorey vegetation influence the effectiveness of riparian woodland buffers to control fine sediment pollution. The design and management of buffers are therefore important to maximise their effectiveness. This includes taking into consideration erosional features like gulley formation within the buffer itself. Understorey vegetation can provide useful roughness against surface run-off but if it is limited by too much shade, this will reduce the buffer's sediment filter functionality (Feld *et al.*, 2018). Too much shade suppressing understorey vegetation can also lead to more bank side erosion. Therefore, to maximise the stabilising effect (as well as filtering effect), the right tree species mix, and density is also required (Nisbet *et al.*, 2011).

The effectiveness of riparian woodland buffers to mitigate lateral sediment transport is very dependent on location (Feld *et al.*, 2018). Riparian management across the entire stream network subjected to lateral sediment inputs is therefore necessary. Results from catchment studies involving model simulations suggest that riparian buffers have great potential to reduce fine sediment pollution, if buffer density in the catchment achieves 70% (Feld *et al.*, 2018). A catchment scale approach is thus required for the control of sediment pollution.

Riparian buffers have limited ability to mitigate sediment pollution that has occurred upstream, unless part of approaches to improve floodplain connectivity and overbank retention of flood waters in e.g. bunded and wetland areas (Feld *et al.*, 2018, Ngai *et al.*, 2017). Therefore, to have a significant effect on stream water quality continuous riparian buffers should be placed high up in the watershed (Schultz *et al.*, 2003).

3.1.5 Capturing pesticides

Functional processes

The main biophysical processes which underpin the function of riparian buffers in general to control pesticide pollution which show positive influences in study results include physical trapping via canopy interception, deposition and infiltration and soil chemical and physical processing via retention onto soil surfaces and microbial processing (Arora *et al.*, 2010; Stutter *et al.*, 2020). Riparian woodland can intercept aerial drift of pesticides, trap pesticides bound to sediment in run-off and remove pesticides from drainage waters through a number of natural processes within woodland soils, including by tree uptake (Lowrance *et al.*, 1984; in Nisbet *et al.*, 2011).

Measured effect

There are a moderate number of studies which measure the effects of capturing and retaining pesticide pollution by active tree planting management in riparian buffer zones (Stutter *et al.*, 2021) There is a moderate level of evidence for the efficacy of these measures in relation to the number of studies (n<5) and studies showing a consistent positive effect for the inclusion of trees, relative to grass only, riparian management buffer zones at plot and field level (as reviewed by Stutter *et al.*, 2021). The earlier review of pesticide retention by Arora *et al.,* (2010) includes forested buffer studies in the U.S. in the metadata, however the review fails to draw out the specific action of forests, or tree planted buffers relative to grass vegetated buffers in the discussion.

Woodland shelterbelts and riparian buffers can be a highly effective measure, achieving reductions in spray drift of between 60 to 90% (Ucar & Hall, 2001; Lazzaro *et al.*, 2008) (in Nisbet *et al.*, 2011 & Stutter *et al.*, 2020). Both a mature, managed woodland buffer (50 m wide) and a newly restored woodland buffer (38 m wide) achieved almost complete pesticide reduction from spray drift (Lowrance *et al.*, 1997; Vellidis *et al.*, 2002) (in Nisbet *et al.*, 2011). Walklate (1999) reported typical drift reduction efficiencies of 86% to 91% for a seven metre-high windbreak of alder trees.

Studies in the USA have assessed the effectiveness of riparian woodland buffer zones at protecting stream waters from aerial pesticide applications to forest stands on the adjacent land (Nisbet *et al.*, 2011). A major study by Dent & Robben (2000) investigated the impact of aerial applications of herbicides and fungicides to forest areas draining to 23 different sized streams across three geographical regions in Oregon. All sites contained overstorey riparian buffers. They found no evidence of substantial adverse effects on either bank vegetation or in-stream water quality, with no pesticide detected at concentrations > 1 part per billion method detection limit in the studied streams. However, sampling was limited to pre and immediately post pesticide application (15 minutes, two, four, eight and 24 hours after application) and did not consider any delayed effects e.g. following a major rainfall event (in Nisbet *et al.*, 2011).

Factors influencing effectiveness

The width and the structure of riparian woodland buffers affect their ability to reduce pesticide losses to water bodies. Studies have shown windbreaks and riparian buffers to give almost complete protection when designed correctly. Effectiveness of trees in trapping aerial pesticide drift can be complicated by local airflow patterns (Ucar & Hall, 2001) which are influenced by tree species, tree height and leaf stage.

The wide range of properties of different pesticide chemical must be considered, the most important of which being the application styles, timing and seasonality of applications, partitioning between (soil) solid and water phases that affects the pathways (e.g. surface runoff vs subsoil and soil drainage) and ultimately fate and residence time in riparian woodland for degradation processes.

Water can infiltrate up to five times faster in restored six-year-old wooded buffers than in row cropped fields or heavily grazed pastures, increasing the residence time and ability of the wooded buffer to treat pesticides through breakdown in the soil (Schultz *et al.*, 2003). However, the pesticides may affect the biological processes that help breakdown pesticides, and other functional processes in the soil.

3.1.6 Capturing pathogen contamination

Functional processes

This section reviews evidence relating to riparian buffers in general as no studies in relation to woodland riparian areas were found. The main biophysical processes which underpin the function of riparian buffers in general to capture pathogens which show positive influences in study results include physical trapping via deposition and infiltration and soil chemistry and biological processing via retention onto soil surfaces and microbial processing (Stutter *et al.*, 2020).

The ability of the soil to attenuate microbes is influenced by infiltration rates. Water infiltrating fine pores of the soil enable microbial attenuation and increases contact with internal reactive surfaces that enable attenuation. Large pores such as cracks, worm holes and large pores reduce the time for microbial reaction (Collins *et al.,* 2007). However, rooting, especially by trees, creates larger soil pores, increasing infiltration capacity (Stutter *et al.,* 2020). It is not clear whether these large pores reduce or increase microbial treatment given the importance of soil contact time identified by Collins.

Artificial subsurface soil drainage of fields enables runoff to bypass buffer areas. Plot studies of grassland buffers based on sampling under both natural and simulated rainfall for *E. coli* and Campylobacter found that the artificial drains carried most flow and microbes. However, heavy intense rainfall did generate surface runoff and carried significant numbers of both microbes, suggesting that riparian buffers may be worthwhile on such land (Collins, 2005), although woodland buffers were not tested.

Fencing to exclude livestock from stream channels and a proportion of riparian land has the potential to be a particularly effective measure in reducing the faecal contamination of pastoral streams. Not only does this prevent the deposition of faecal material directly into streams and near-channel contributing areas; the dense vegetation associated with riparian buffer strips reduces the momentum, thereby increasing infiltration and promoting the entrapment of faecal material and other agricultural pollutants (Parkyn 2004).

Measured effect

The Stutter *et al.* report (2020) found that few studies have examined trapping of pathogens or faecal indicator organisms (FIOs) in run-off. A range of 53% to 100% removal across varying buffer widths has been reported (Collins *et al.,* 2009), but there are strong interactions with concentrated flow occurrence and management factors like fencing. Success seems most likely where livestock are excluded from the buffer and where slope, soil and vegetation promote infiltration of run-off within-field. However wooded buffers have not been specifically tested.

Factors influencing effectiveness

Reviews of the effectiveness of riparian buffer strips in attenuating microbial contamination were found to be affected by slope, soil type, buffer width and type of faecal material, the degree of attachment of microbes to the soil and rate of runoff (Collins *et al.,* 2007). Vegetation type is not identified as a key factor. There is a risk that trees attracting animals for shade increases the risk of faecal contamination and poaching in the riparian area if the woodland is not fenced, leading to increased transfers of soil and pathogens to the water course with surface runoff. Therefore, unfenced riparian woodland in pasture increases the risk of faecal contamination (Collins *et al.*, 2007).

3.1.7 Controlling excessive algae and periphyton

Functional processes

Algae are aquatic organisms that contain chlorophyll and can photosynthesise. In lochs, and slow flowing rivers with long retention times, phytoplankton will dominate; this is microscopic algae that photosynthesises and lives suspended in the water. However, in the majority of Scottish fast flowing rivers, phytoplankton are minimal and phytobenthos, also known as periphyton, will predominate[11]. Although nutrients, in particular phosphorus, are generally the main factors controlling periphyton growth in rivers, light, rate of flushing and disturbance will also be of importance, together with grazing and type of substrate. Riparian trees shade the watercourse, affecting light levels which influences communities of periphyton.

For example, *Cladophora* is a filamentous alga that is part of the periphyton community in fast flowing rivers. It provides a structural habitat for other species, including various epiphytes and food for grazers such as Caddis fly larvae. Under nutrient-rich conditions, it can become dominant, leading to large filamentous growths which shade out other species. However, ambient light can control its dominance (Dodds & Gudder, 1992; Dudley & D'Antonio, 1991). Therefore, one of the impacts of shading from trees is to limit the growth of filamentous algae such as *Cladophora*, allowing more shade-tolerant species of the periphyton community to dominate (Kelly *et al.*, 2016).

Light also has a limiting effect on phytoplankton, which is associated with algal blooms found in slow flowing rivers with a residence time of over four days, according to Environment Agency risk analyses. The main factors affecting risk were sunlight duration and water temperature. River shading from riparian trees was identified as a means to manage sunlight duration and water temperature (Bowes *et al.*, 2019).

Measured effect

In mesocosm experiments in New Zealand riparian planting with 60%-90% shading on 12 replicate channels was found to control periphyton growths in pasture streams, together with relatively high invertebrate grazing densities effects (Quinn *et al.*, 1997). The New Zealand study found a difference between the taxonomic richness of the channels with natural riparian woodland shade and the artificial shade used in the experimental shaded channels, such as litter inputs which compensate for lower productivity associated with lower light levels (Quinn *et al.*, 1997). Similar work by DeNicola *et al.*, (1992) demonstrated that chlorophyll a (a measure of total algal biomass) on gravels in prairie streams in Nebraska correlated with shade effect of between the equivalent of 68% and 81% shade. Triska *et al.*, (1983) also demonstrated a measured reduction in periphyton biomass development of between 66% - 92% in channels from northern Californian stream.

For control of *Cladophora* specifically, research on the River Avon in Canada found the average level of shading of 71% was effective in reducing growth by 50 to 91% in the controlled replicate channels. Under natural tree canopies on the same river, with 48 to 83% shade, reductions were comparable at 60 to 74%. However, high temperatures greater than 20°C were the main control in summer months. Temperatures between 15-20°C favour Cladophora growth (Demal & Fortin, 1987). Therefore, riparian woodlands with 50-90% shade act in combination with reductions in phosphorus to limit *Cladophora* dominance and other excessive algal growth in nutrient-rich waters.

The Environment Agency's risk model for eutrophication and algal blooms for English rivers found that river shading by trees may be particularly effective at reducing the adverse impacts of blooms in locations where water temperature thresholds are ranging from 5°C to 25°C. Phosphate concentrations were not found to be effective in reducing the risk of algae blooms due to concentrations being above threshold levels limiting growth (Bowes *et al.*, 2019). Research on the River Thames found that once the soluble reactive phosphorus (SRP) threshold of 0.1 mg/L (100 µg $l^{-1)}$

[11] Phytobenthos is an algal community contains epiphytes, which grow on aquatic plants, epilithon which grow on rocks, episammon which grows on sand, and epipelon which grows on mud. It also contains cyanobacteria. Periphyton is synonymous with phytobenthos and is the term generally used as the major source of primary production in rivers.

had been reached, the shading of the river channel by riparian trees was required to aid further reductions (Bowes *et al.*, 2012).

Modelling of rivers in Northeast England using QUESTOR [12] found riparian shade to be even more effective than nutrient reduction through sewage treatment. In combination, both management options led to a reduction of phytoplankton peak biomass by 44% as compared to 11% at unshaded reaches. (Hutchins *et al.*, 2010). The test catchment had a SRP level of 0.21mg/L, which exceeded the SRP threshold identified by Bowes *et al.*, (2012), which would have influenced the effectiveness of reducing phosphorus inputs from the sewage treatment works. The results were modelled with no empirical evidence gathered for the impact of a change in tree growth in the system. However, it indicates the potential significance of combining riparian shade along with other management measures that reduce nutrient inputs to manage algal blooms.

Factors influencing effectiveness

The majority of Scottish rivers tend to be smaller and fast flowing than English rivers so are unlikely to have a build-up of phytoplankton associated with slow flowing impounded rivers. Scottish rivers, however, may get excessive algal and periphyton growths where rivers are sluggish and dead zones occur. The impacts may be exacerbated in rivers with a lack of riparian tree growth providing shade and higher summer temperatures associated with climate change. However, Scotland's upland headwaters, whilst lacking tree cover, have lower phosphorus concentrations than in English rivers.

Riparian woodland may regulate to some extent the processes of: shading affecting light levels and water temperature; altered runoff rates during storms affecting bed scouring; baseflow; water temperature and water residence time in stream reaches; and nutrient inputs. (Feld *et al.*, 2018). However, at larger catchment scales there is a need to consider the length and continuity of the wooded zones to induce effects like cooling. Also, to consider that water temperature increases proportionally with river width as represented by Strahler stream order (Broadmeadow and Nisbet, 2004). Feld *et al.*, (2018) described the evidence underpinning how the design of riparian woodland (width and length) effects in-stream water temperature as well as other natural geo-climatic co-variates such as latitude, precipitation, stream size and current (see Section 3.9 for more details on shading and temperature).

3.1.8 Evaluation of evidence

Strength of evidence (based on quality of studies)

Controlling nutrient pollution: There is a strong knowledge base for the biophysical processes provided by riparian woodland buffers to retain nutrients. Once short-duration studies are discounted, there is **strong** empirical evidence that riparian woodland buffers reduce the amount of nitrates leaching to surface waters from adjacent nitrogen source zones at the field scale when compared with grass-only riparian margins or cropland. There is **strong** empirical evidence that riparian woodland buffers reduce phosphorus. However, whilst phosphorus attached to sediment is effectively reduced, levels of dissolved reactive phosphorus may increase, limiting the effectiveness of wooded buffers to manage phosphorus. There is evidence from the SWAT hydrological model that nitrogen and phosphorus loading is lower from deciduous and mixed forest compared to agricultural catchments (as source area) in continental Europe.

[12] QUESTOR (QUality Evaluation and Simulation TOol for River systems) is a daily river quality model which combines river flow and water quality data. It uses chlorophyll–a as a surrogate for river phytoplankton biomass. It is used to represent flows and chemical inputs to a network of river channels and test management scenarios against a baseline river system.

Capturing sediment pollution: The biophysical processes underpinning the ability of riparian woodland buffers to retain sediment pollution are well understood. There is **strong** empirical evidence from site-based experiments that riparian woodland can reduce suspended solids compared to controls at the field scale. For floodplain woodlands, the evidence for reducing diffuse pollution by enhancing siltation and retaining sediments is **moderate** based on international empirical evidence. However, there is less quantified data available in Scotland and the lack of mature floodplain woodland restricts research. There is **moderate** evidence from the SEDMAP model that strategic planting in upland catchments reduces coarse sediment loading at the catchment scale significantly. There is evidence from the SWAT hydrological model that sediment loading is lower in deciduous and mixed forest compared to agricultural catchments (as source areas) in continental Europe.

Stabilizing riverbanks: There is **very strong** empirical evidence of the biophysical processes that tree roots stabilise riverbanks from the international literature. There is **strong** evidence of the measured effect to show that banks lined with riparian trees are effective to reduce bank erosion, including from major flood events, and fine sediments from bank erosion in waterways. There are multiple lines of empirical evidence based on English and Canadian sub-catchment studies.

Capturing pesticides: The biophysical processes that underpin the ability of woodland buffers to capture pesticides are well understood. There is **strong** empirical evidence that riparian woodland buffers can trap aerial applications of pesticides from adjacent land with multiple lines of moderate evidence from the international literature. The evidence for quantified pesticide load reductions in waterways remains **moderate** as it is only based on a few studies and there have been no studies in the UK.

Capturing pathogens: There are **weak** lines of empirical evidence from field studies that riparian buffers can trap pathogen or faecal indicator organisms based on case-control designs with plot studies, however woodland riparian areas were not specifically considered. 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. There is no data that quantifies pathogen load reductions in waterways.

Controlling excessive algae and periphyton: Whilst evidence of the effects of trees on shading, light and temperature are **strong** the interactions with water flow, seasonality and nutrient levels are not well understood outside of a few mechanistic study areas. Some of these have involved flow-regulated rivers with long residence times or higher nutrient systems beyond upper thresholds of algal response to P concentrations. Although lacking in direct evidence for woodland change effects from modelled studies for Scotland, comparable work from New Zealand suggests a similarly **strong** evidence for equivalent fast flowing Scottish river types.

Relative effectiveness rating

Some research projects utilise expert judgement to inform understanding across complex environmental knowledge requirements such as the relative effectiveness of mitigation measures for multiple benefits aspects. Whilst not a direct pathway from classical science of monitoring, experiments and modelling to evidence, such expert processes can rapidly cut across complex aspects and combine researcher understanding of scientific literature evidence with practitioner personal field evidence. The 3D buffers report by Stutter *et al* (2020) undertook such scoring via workshop of nine experts across five packages of riparian buffer measures (grass, wildflower and wooded buffers, then engineered raised ground and subsurface interception buffers), assuming a width of six metres and following best management practice. In each of the sections for specific pollutants, a summary of the results of the relative effectiveness scores (ranging from 5 (very good) to 1 (very limited) is provided below.

Controlling nitrogen pollution: a **moderate** rating (score 3 out of 5) of relative effectiveness of man-made riparian woodland buffers in the capture and uptake of nitrogen was assigned by experts compared to a very limited confidence (score 1) for grass buffers (Stutter *et al.*, 2020). Engineered buffers which captured sub surface flow were given a higher level of confidence rating of good (4) in comparison.

Controlling phosphorus pollution: a **moderate** rating (score of 3 out of 5) of relative effectiveness of man-made riparian woodland buffers to capture and retain phosphorus was assigned by experts compared to very limited confidence (score 1) in grass buffers (Stutter *et al.*, 2020). Engineered buffers which captured sub surface flow were given a higher level of confidence rating of good (4) in comparison.

Capturing sediment pollution: a **moderate** rating (score 3 out of 5) in the effectiveness of man-made riparian woodland buffers to control soil loss and retain sediment has been assigned by experts compared to limited confidence (score 2) for grass buffers (Stutter *et al.*, 2020). Only engineered buffers scored higher (4) due to sediment traps giving more likelihood of controlling aggressive erosion or fine clay particles.

Capturing pesticides: a **high** rating (score 4 out of 5) in the effectiveness of man-made riparian woodland buffers to retain pesticides has been assigned by experts compared to very limited confidence (score 1) for grass buffers. No other considered riparian buffers scored greater.

Capturing pathogens: a **moderate** rating (score 3 out of 5) in the effectiveness of man-made riparian woodland buffers to provide a barrier and retain FIO was assigned by experts, but this was no different from all other styles of considered buffer zones (Stutter *et al.*, 2020).

Limitations & research gaps

The prolific body of literature concerning management buffers applies to generally narrow (several to 10-20 m width) riparian edges adjacent to cropland. Thus, evidence draws heavily on a specific type of tree-planted mitigation measure (Stutter *et al.*, 2021) distinct from longer established woodland and river restoration actions addressed also in Feld *et al.* (2018). It is also important to note that often such evidence looks most often at plot scale functions of wooded riparian zones and not at the scale effects of accumulated riparian woodland which bring benefits for stream reaches and, especially, larger catchments. There is thus a lack of evidence to link clean water outcomes to woodland management or planting actions at the catchment scale in Scotland.

There are other shortcomings of evidence in terms of the limited studies that have controls in either space or time (Stutter *et al.*, 2021) and especially with regard to absence of before intervention data for the definitive Before-After-Control Impact (BACI) study design (Feld *et al.*, 2018).

Even though outcomes are desired at catchment scales, the evidence becomes more uncertain as scales increase due to lack of replicating mitigation measures outside of individual study locations. There are some studies that investigate wider source-transport-receptor processes and complexities of bigger catchments; often modelling is used for upscaling. In the managed buffer zone literature, there is a lot of variation in studies. For example, out of 45 studies on sediment across buffer zones generally, soil profile was considered in 5% of studies; plot scale considered in 73% of studies, 100m reach scale (8% of studies) and catchments scales (8% of studies) (Stutter *et al.*, 2021). There are more catchment studies done on sediment and total phosphorus (P) rather than other pollutants such as on coliform pathogens and pesticides.

Even with monitoring data and quite widespread actions of riparian buffer strips, the effects at catchment levels are complex to unravel (Bergfur *et al*. 2012) and where trees are influential on effects of runoff control, shade and bank stability there are timescales required to manifest effects (Stutter *et al.*, 2021). A number of studies on riparian woodland buffers have found it difficult to detect significant changes in macroinvertebrate communities as a measure of cleaner water status such as in the Tarland catchment in Aberdeenshire (Bergfur *et al.*, 2012). A similar lack of improvement in invertebrate communities was found from analysis of different ages of riparian woodland buffers on pasture streams in New Zealand. However, one stream studied did show a significant improvement in invertebrates compared with a nearby pasture stream without a buffer. The riparian buffer had 25-year-old plantings and the whole stream length planted, providing shade to the stream. The research concludes that improvement in invertebrate communities appeared to be most strongly linked to lower stream temperature, suggesting that restoration of in-stream communities would only occur after canopy closure and after protection of headwater tributaries. This was particularly evident in lowland streams where catchment influences had a greater impact than local riparian influences (Parkyn *et al.*, 2003). The lack of data on ecological and chemical status of freshwaters in headwater streams is very limiting and a significant evidence gap (UK Parliament Post, 2022).

There is a need to understand better how design (composition & structure including density, age & species) and management influences the effectiveness of riparian woodland buffers to mitigate diffuse pollution in the UK. This includes taking into consideration pathways for pollution swapping. More research is needed to understand the release of greenhouse gases associated with denitrification and the potential for pesticides to wash off leaves into the water course.

Further research on the design of riparian woodland buffers to maximise sediment retention capability (e.g. in terms of width and length of buffers for different soil and slope combinations) is required. This includes further research on the right species mixes to reduce bank erosion at different locations in different catchment types in Scotland.

Effects of woodland measures on diffuse pollution are scale-dependent and conditional on the situation further upstream in the continuum as there may be a large pollution source upstream (Feld *et al.*, 2018). It is important to consider the nature of local pollutant sources and pathways in relation to the catchment context.

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.

Sediment fingerprinting and SCIMAP (SCIMAP - Diffuse Pollution Risk Mapping) are useful tools[13] which could be used in combination with each other and in combination with opportunity mapping to help build an evidence base.

[13] Sediment fingerprinting involves geochemical analysis of soil and river bed samples to determine the proportional contributions of different sources (which can be soil from different land use types, eroding riverbanks, or bed material from upstream reaches) to a particular receptor (normally a specific reach). SCIMAP is a risk mapping tool that uses landscape properties (rainfall, topography, landcover type and hydrological connectivity) to determine the relative risk of surface erosion and delivery of sediment to the river network. If sediment fingerprinting has identified a catchment contributing a lot of sediment, a quick SCIMAP run can identify possible source areas within the catchment.

As part of its diffuse pollution impact monitoring work, SEPA uses a macro-invertebrate sediment-response metric (Proportion of Sediment-sensitive Invertebrates, PSI, and the more recent E-PSI) to assess the degree of deposited fine sediments on riverbeds. This metric developed by Extence *et al*., (2011), with further development (E-PSI) by Turley *et al.*, (2015) could assist in the identification of areas for prioritisation of riparian woodland once sediment sources have been identified, and to assess river improvement, following restoration of riparian woodland.

Further tools are needed to help with the design of river woodlands at a landscape scale and to identify riparian buffer areas in a functional sense. SEPA produced a map to identify sections of rivers where hydromorphological processes can be recovered with low levels of intervention. These results will be combined with available space for riparian vegetation to identify places where complete restoration is achievable at low intervention. This should include identification and mapping of groundwater vulnerable source zones.

The application of modelling tools (such as SEDMAP) to assess the impact of strategic planting in upland catchments to reduce coarse sediment delivery to watercourses would be helpful.

To be beneficial, scale-dependent effects require coordinated management at both the riparian and catchment scale. Riparian buffer management thus needs to be accompanied by nutrient measures in the wider catchment. Models suggests that riparian management alone can buffer only up to 50% of the nutrients that enter the stream system. The other half requires nutrient reduction options (e.g. fertilizer management) at the broad scale.

The QUESTOR modelling study in River Ouse catchment in NE England is limited by field data but does offer a potentially very valuable tool to assess the most 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 of riparian shading in the headwaters is to help with mitigation.

3.2 Climate action: adapting to water stress and drought

3.2.1 Overview of benefit

This benefit focusses on how river woodlands may help with adapting to water stress during dry periods and drought. Healthy woodland soils with good structure can store more water and in the right place could contribute to adaptation. Drought is associated with prolonged dry conditions and can occur in both summer and winter. Dry hot weather can then lead to dry soil conditions and a lack of water (water scarcity). Research investigating drought in Scotland has indicated an increasing prevalence of water scarcity, particularly during the summer months and especially affecting areas which have limited water storage (Gosling, 2014). UKCP18 predict that climate change has already increased the chance of seeing a summer as hot as the summer of 2018 where daily temperatures exceeded 30°C to between 12 and 25%. With future warming, hot summers by mid-century could become even more common, near to 50%. A study on drought projections for Scotland for years 2021-2040 further show that extreme drought events are likely to increase across Scotland from the baseline data (1981-2001) of one every 20 years to one event every three years and one up to every 1.7 years in the driest locations (Kirkpatrick Baird *et al.,* 2021).

This section focuses on the role that riparian and floodplain woodland may have in adapting to drier periods and drought via two main functions: modifying local climate conditions; and maintaining water yields and low flows. The ability of river woodlands to adapt to long term drought is also discussed.

Beneficiaries

River woodlands have the potential to contribute to adapting to drier conditions by providing shade, cooling air, maintaining soil moisture regimes and providing natural water storage. Agroforestry is recognised as an important land-use option for drought adaptation which can be practiced within the riparian zone. A greater understanding of how different tree species and woodland types within the catchment affect soil moisture regimes and water supplies will be of interest to land managers, planners and Scottish Water for resilience planning.

3.2.2 Modifying local climate conditions

Functional processes

In summer drought conditions, air temperatures can be high and trees can have a cooling effect. The cooling effect of trees comes largely from shading and evapotranspiration. The factors that modify temperature and humidity under woodlands include:

i/ Radiation (light):
Trees reflect, absorb and transmit sunlight via their canopy. The effect depends on canopy structure and leaf density with less short-wave radiation (light) reaching the ground (shading), but more long-wave radiation reaching the ground. This results in warming of the tree canopy (Thomasius & Schmidt, 1996, Wohlleben, 2018) and usually a cooler ground surface, with reduced diurnal changes.

ii/ Evapotranspiration: Through the process of evapotranspiration, some of the energy absorbed by trees evaporates water within their leaves, cooling them and the surrounding air. Evapotranspiration is higher in the tree canopy than closer to the ground due to higher leave density, more solar radiation and stronger air movement (Thomasius & Schmidt, 1996). The cooling effect from shading on the other hand can lead to less evaporation in forests (Wohlleben, 2018).

iii/ Air movement (wind): Shading by leaves reduces drying at the soil surface and retains humidity coming from the river in the air under the canopy. In woodlands, wind speed is, depending on tree density, reduced to 10-20% compared to the outside. Thus, the warmer air is more contained closer to the ground than in and above the canopy, and overall humidity is also contained (Thomasius & Schmidt, 1996). In floodplain forests, the levels of dew interception by trees can be greater because of the proximity of the river thus potentially enhancing the positive micro-climate effect under the trees (Hughes, 2003).

This combination of different factors and their complex interaction determine the temperature and humidity of river woodlands (Thomasius & Schmidt, 1996, Hughes, 2003). This cooling and higher humidity helps with reducing the impact of drought and reduces water stress to plants.

The impact of water stress on plants is further reduced by hydraulic lifting and redistribution of water. This is a process where roots that span soils with different water potentials act as conduits that transfer water from lower wet layers to upper drier layers of soil (Hughes, 2003). Plants, especially with deep roots are able to lift up or redistribute water to the upper soil layers, potentially acting as "bioirrigators" to adjacent plants (Bayala, 2020). The redistributed water can be important in regulating plant water status, but also in increasing the survival and growth of adjacent plants. Hughes (2003) describes in a global review on floodplain woodland (for the European FLOBAR2[14] Project) how

[14] FLOBAR2: **FLO**odplain **B**iodiversity **A**nd **R**estoration: Integrated natural science and socio-economic approaches to catchment flow management. Department of Geography, Cambridge » FLOBAR2 - Floodplain Biodiversity and Restoration:

the volume of hydraulic lifting can influence the seasonal water balance of whole plant communities of floodplain woodland ecosystems as well as individuals, promoting growth and productivity and influencing nutrient recycling.

In agroforestry, hydraulic lifting is also surmised to increase the survival and growth of associated crops in mixed systems (Bayala, 2020). A global systematic review on hydraulic redistribution by plant roots (which included tree species), describes how in some ecosystems, where only a small amount of water can be moved by hydraulic lifting, it can still be ecologically significant for plant survival. For example, by maintaining fine roots, mycorrhizal hyphae, and root–soil contact, or preventing embolism, and thus at a population and community scale, this may influence hydrology over the long term (Neumann & Cardon, 2012). It is noted that this review, did not cover native tree species from northern European temperate climates.

The FLOBAR report explains how hydraulic lifting amongst floodplain trees can buffer plants against water stress during dry periods but if soils become too dry, the tree roots cannot extract soil moisture anymore (Hughes, 2003). Furthermore, the alluvial sediments are critical for the retention and provision of moisture during dry periods and such deposition is aided by the physical presence of trees. When the sap flow in three adult oak trees in a floodplain forest at the Elbe River in Lower Saxonia (Germany) was measured throughout a growing season, where there was little precipitation in summer and the average temperature was low, soil moisture was in a range which facilitated low rates of hydraulic uplift (Eller, 2015). The drought response of 25% of all investigated oak, elm and ash sapling transects were affected by their distance to the adult tree. Findings from further laboratory experiments on floodplain woodland elm and ash saplings found that hydraulic lifting was occurring but competing with night- time transpiration. One of the mechanisms of more drought resistant tree species, involves their ability to shut down transpiration at night, to conserve water and maximising the benefit from hydraulic lifting to maintain root structures, mycorrhiza and support other younger trees (Eller, 2015).

Measured effect

Results from field experiments carried out by RWTH Aachen University found that the floor of a native deciduous forest in Germany on a hot day in August (37°C) was up to 10°C cooler than that of a regularly thinned coniferous plantation, two miles away (Wohlleben, 2018). The degree of this cooling effect was attributed to the forest biomass which also contributed shade. The more living and dead wood there is in the forest, the thicker the layer of humus on the ground and the more water is stored in the total forest mass. There is some additional data from Germany which suggests a cooling effect under woodland. Differences in air temperature measured at two metres under an 80 year old mixed pine broadleaf and at a clearing showed that the temperature was always lower in the woodland, the temperature difference increasing with higher air temperature. At 4°C in the clearing was 0.9 C cooler and at 30°C in the clearing was 3.75°C cooler in the woodland (Burschel and Huss, 1997).

Agroforestry with tree fruit and nut species and intercropping enables farmers to use the hydraulic lifting and cooling effects to benefit production. For example, Kuyah *et al*. (2016) reviewed the roles of trees on agroforestry farms in semi-arid sub-Saharan Africa and found that, in most cases, trees had beneficial effects on associated crops by enhancing soil water availability in 58% of the studies considered in their review. The net effects that species engaged in hydraulic redistribution have on their neighbours is still unclear (Prieto *et al*., 2012). There are reports of positive, neutral, or even negative effects depending on ecosystem type, plant life form or whether donor and receiver species shared common ecto- and endomycorrhizal networks. Common mycorrhizal networks are strongly involved in water and nutrient sharing between plant species (Allen, 2007; Montesinos-Navarro *et al*., 2019). There is currently poor quantification of the volumes of water transferred between species. Although the hydraulic lifting process as a part of silvoarable systems can be applied to many tree species, most of the evidence is from semi-arid countries and not well understood in temperate systems (Tim Pagella, *pers. comm*). There are a limited number of studies from Europe such as in Montpelier in France, that have demonstrated that intercropping wheat systems with walnut will buffer those systems from the effects of drought, but this is related more to the shelter function of the tree rather than a hydraulic lift effect.

Factors influencing effectiveness

Tree species characteristics influence their ability to provide shade. A wider canopy and high density of leaves and branches in the crown of the tree will provide more shade. Generally, the higher the rate of evapotranspiration, the more cooling a tree will provide. A higher tolerance to drought amongst certain species can ensure that evapotranspiration will occur for longer with an ability to conserve water at the same time.

When determining the impact of forest on local climate each factor (radiation, evapotranspiration and wind) varies over the day and year. The structure and composition of the woodland itself (species, age, density, with or without leaves) influences the impact as well. This makes comparisons of air temperature between open land and woodland difficult (Thomasius & Schmidt, 1996). It also results in complex temperature profiles within the woodland, varying during the day and seasons (Otto 1994).

Hydraulic lifting (HL) is influenced by physical and biological factors (Neumann & Cardon, 2012). Physical factors include the characteristics of the soil, gradients in soil water potential and depth of groundwater. Soil texture influences the potential magnitude of hydraulic lifting, with sandier soils promoting less HL. A soil water potential gradient must develop for hydraulic lifting to occur. As surface soils dry, HL often initially increases (as the driving water potential gradient develops in the soil column), reaches a maximum and then either decreases or plateaus.

The biological factors which influence hydraulic lifting include the root structure, transpiration rates and drought adaptations of tree species. One of the key factors controlling effectiveness of hydraulic lifting to address drought is the night-time transpiration rate (Eller, 2015). However, this is not always the case, the strengths of the whole shoot and root–soil system sinks for water determine the outcome of competition for water (Neumann & Cardon, 2012).

Tree species with dimorphic root structures with deep tap roots as well as shallow root system tend to use HL, although this is not always the case (Neumann & Cardon, 2012). The tap roots allow groundwater to be assessed where water is not available in the topsoil horizons. Groundwater has been noted as important for strong upward HR in oak in southern Portugal. In the Sahel, trees used in silvoarable systems have deep tap roots to match deep groundwater systems there. In Scotland, only some trees have tap roots (e.g. Oak species). The search for water by roots will only be possible if there are no barriers such as dry gravel layers between the roots and deeper, moist layers. If the soil is shallow, then the effect of hydraulic lift is likely to be minimal. Trees that have been happily sourcing water from the surface will also struggle to suddenly switch to deeper water systems should a drought occur, so mycorrhiza are critical. Where there is deeper soil, sub-surface compaction may also limit root growth. Historical land-use/management can create a semi-impermeable soil layer (e.g. plough-pans) limiting the vertical extent of roots, the effects of which can take many years to reverse (Archer *et al.*, 2015). Seasonal perched water tables would also limit root growth. Topography will also play a part in determining root depth and whether roots are 'reaching' for groundwater, regardless of climate (Fan *et al.*, 2017).

Ecohydrological modelling tools could be used to assess rooting depths and moisture gradients in the riparian zone where these factors can be limiting to aid appropriate planting. The RibAV model, for example, is used in semi-arid areas to predict locations of different riparian vegetation types herbaceous, woody and terrestrial dryland species, and to understand the impact of different water resource management strategies on this vegetation (García-Arias *et al.*, 2014).

3.2.3 Maintaining water yields and low flows

Functional processes

When investigating the role of woodlands (& river woodlands) in maintaining water yields and low flows, it is important to consider the water use of trees and their water storage ability. There is a very strong understanding of the biophysical processes underpinning how trees use water which includes translocation (by tree roots), interception (by leaves, branches and trunks) and evaporation (Nisbet, 2005). The water use of trees and subsequent impact on water yields will be determined by evapotranspiration rates (total loss of water by evaporation) as well as other abiotic factors (Nisbet *et al.*, 2005).

Some studies show that trees can contribute to drought conditions via increased evapotranspiration (Takata & Hanasaki, 2020) and creating, via their roots, deeper drainage, thus reducing the ground water table depth (Stockan *et al.,* 2012). Interception losses can be quite variable amongst broadleaves related to differences in canopy density with the lighter canopies of species such as ash and birch having lower interception loss than heavier canopies of oak or beech (Nisbet, 2005). The largest difference has been found in willow and poplar which can sustain high transpiration rates of 500 mm yr^{-1} in wet soil conditions (in Nisbet, 2005). In these species, sap flows through numerous tree rings (rather than just the outer ring as found in many tree species), and these additional active tree rings can enhance the water consumption if more water is available (Hughes, 2003). However, when river levels are low, water consumption can decrease considerably, to about half of water used during a high-water period (in Hughes, 2003). More research is required to understand the differences in evapotranspiration rates and water use of different species suitable for planting riparian and floodplain woodlands and to assess impacts on water yields.

Woodland soils can receive, soak up and store water (Nisbet *et al.*, 2011). The moisture can be released slowly particularly if the woodland has deep soil layers as found in old growth deciduous woodland which would be also applicable to mature native riparian woodlands. This has the potential to mitigate against periods of drought as well as heavy rain and flooding by reducing overland flow. The ability of woodland soils to soak up and store water is dependent on soil infiltration rates and sufficient pore space determined by the soil type and the health of the soils with a well-structured soil holding more water (see section 3.6.2).

A secondary benefit of the retention of floodwaters by natural floodplain woodland could be the potential enhancement of low flows as the retained water, in the form of surface pools and shallow groundwater, is slowly released to the river system (Kerr & Nisbet, 1996). The expansion of wetland features within floodplain woodland is likely to be important in this respect (Kerr & Nisbet, 1996). Although little attention has been paid to the role of natural floodplain woodland in maintaining river low flows, some research suggests wetlands, with water stored in pools, side channels and wetland soils, can form key sources of shallow groundwater for the maintenance of dry season low flows (McGlothlin *et al.*, 1988). Hughes (2003) review of European floodplain woodlands also describes how water that is held up on the floodplains during flood events also seeps into the soils and can help to recharge aquifers.

Measured effect

It is commonly reported that trees have the ability to use more water than most other types of vegetation. When both interception and transpiration were considered together, assuming an annual rainfall of 1000 mm, Nisbet (2005) found that the range of annual evaporation losses (mm) for broadleaves (400-640mm) were similar to grassland (400-600mm) and heather (360-610mm), lower compared with conifers (550–800 mm) but higher than for arable (370-430mm).

There are just a few studies which have quantified the impact of the water-use of broadleaf species on groundwater recharge but that has been limited to English studies with varying results thought to be because of differences in soil/geology and species related factors (Nisbet *et al.*, 2011). A number of studies have modelled the impact of broadleaved woodland planting schemes on local water resources. Drawing on the results from UK studies both on chalk and sandstone, Price (2005), concluded that the impact on the average annual water yield of an increase in native broadleaved woodland cover from 4% to 40% of the catchment of the public water supply catchment of Loch Katrine in Scotland would range from +1% to -4% (average of –2% for mixed broadleaves) with the application of the Hydrological Land-Use Change model (HYLUC) for three woodland types (beech, ask, oak) (in Nisbet *et al.*, 2011), which indicates a relatively small effect. The average change to the summer yield (April to September) under the same scenario, ranged from 0% to –13% (average of –7% for mixed broadleaves) (Price, 2005), indicating an increase in effect. Price (2005), however, suggests that the average reductions in yield are likely to be overestimates of the impact as the HYLUC model does not account for cloud deposition and gives equal weighing to losses from the heavier foliaged beech and oak woodlands and for the lighter foliaged ash. The accuracy of the model is also limited by broadleaf parameters which come from studies from England.

A few studies have assessed the impact of broadleaved woodland on low flows but those reviewed by Robinson *et al.*, (2003) showed no detectable effect. In conclusion, planting new woodland could potentially reduce the available water yield but with little impact expected on low flows. Large scale planting of conifer woodland poses the greatest risk, especially within dry lowland areas. Planting native broadleaved woodland is likely to have a relatively minor impact on water yield and low flows, although there is a need to strengthen the evidence base in the UK (as concluded in Nisbet *et al.*, 2011).

The evidence of floodplain wetlands and woodlands to help maintain low flows is not quantified. There are hydrological links between wetlands, groundwater and the river, however indications from Scottish studies are that groundwater influenced by river levels affect levels in wetlands on the floodplain. Further research is ongoing on the Eddleston Water and as planted riparian and floodplain woodlands become more established their impact on hydrology will be better understood at low and high flows.

From a study of groundwater and river interaction in the Findhorn Floodplain in Northeast Scotland hydrochemistry and groundwater-level variations show floodplain groundwater is recharged from the river, surrounding hillslopes and direct rainfall infiltration. The river loses water to groundwater as it enters the floodplain; further downstream, groundwater response follows closely river stage giving rise to complex exchanges; near the sea, groundwater continually discharges to rivers, tributaries and ditches. Groundwater flow is largely parallel to the river and mean groundwater residence times vary from 3 years to 20 years. Persistent groundwater flooding occurs within topographical lows and also in the discharge zone. This study indicates that floodplain wetland water levels are regulated by groundwater, affected by river levels rather than movement from wetland storage into the river to maintain low flows (Macdonald *et al.*, 2014). A study of floodplain, groundwater and river interactions in the Eddleston Water, an upland catchment of the River Tweed floodplain, found that groundwater throughout the Eddleston floodplain is closely linked to surface water (rivers, soil water and wetlands). Depending on the local environment and the weather, groundwater can mitigate, exacerbate or cause flooding. The relationships are complex, and the specific contribution of floodplain hollows and wetlands is not quantified (Ó Dochartaigh *et al.,* 2012).

Factors influencing effectiveness

Trees can use more water than other types of vegetation but whether they do and by how much is dependent on many factors, including tree species, location and local climate, soil and geology, woodland management and design, scale of woodland and the type of land cover being replaced (Nisbet *et al.*, 2011). This is summarised well in the Forest Research Information Note on water use by trees (Nisbet, 2005). Evergreen conifers tend to have a greater water use because high interception losses are maintained throughout the year. Soil and geology can affect water use by influencing the amount of water that is available in the soil to maintain transpiration although most tree species are relatively insensitive to soil drying until soil moisture levels become very depleted. Woodland design influences water use through determining the mix of species and crop ages, and the amount of open space. A mixed-aged forest will usually have a lower water use than a single-aged one. The management of a woodland will affect water use; the more developed the understorey and the less it is damaged by felling, then the smaller the change in water use. Scale becomes an important issue when extrapolating the water use of a forest to the level of a larger catchment. As the proportion of the area occupied by forest declines, its 'signature' will be progressively diluted by that of the non-forest land cover.

Research of paired forested and non-forested river sites in poorly drained northern hemisphere sites found that soil properties were more dominant in controlling flows during wet periods and vegetation had greater influence during dry periods. Results showed that soil properties exert a much stronger influence than vegetation on water storage dynamics and fluxes, both at the plot and catchment scale. During drier conditions, more marked differences in soil water dynamics related to vegetation properties emerged, in terms of evaporation and impacts on temporarily increasing dynamic storage potential. However, the potential to influence flows is limited (Geris *et al.*, 2015).

3.2.4 Evaluation of evidence

Strength of evidence (based on quality of studies)

Modifying local climates (shading & cooling air): There is **strong** evidence that trees can have a cooling effect from the biophysical processes of shading and evapotranspiration where shading can also reduce drying at soil surfaces and retain humidity from the river.

Modifying local climate (hydraulic lifting): 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. The hydraulic lifting and bioirrigation process in silvoarable practices influencing vegetation in the riparian zone in semi-arid climates is well understood (with RivAV process based modelling used extensively). However, there is no evidence that tree species in Scotland or temperate climates have similar properties to those in drier climates. Many of the processes are not fully understood and there is mixed effectiveness. There is no evidence for this in the UK and Scotland in relation to silvoarable practices and thus the evidence remains **weak**.

Maintaining water yields & low flows: There is no evidence to suggest that riparian and floodplain woodlands maintain water yields or low flows. There is no evidence that they will have a positive nor negative effect on water yields either. There is **moderate** lines of evidence to suggest that planting native broadleaved species is likely to have a relatively minor impact on annual average water yield at the catchment scale in Scotland but no evidence of any positive effect. There is **weak evidence** for floodplain woodland storing sufficient water to influence low flows, based on the evidence in individual Scottish catchments, but it is inferred from other research on flooding. A global review indicated that there is quantification of negative and positive effects of low flow volume for floodplain wetlands, however this is from climatic zones not applicable to Scotland. Little attention has been paid to the role of natural floodplain woodland in maintaining river low flows in the UK. There are single studies for specific Scottish floodplains which found evidence of flows between rivers, groundwater in the floodplain and floodplain features. However quantified evidence of the impact on low flows of floodplain features was not demonstrated.

Limitations & Gaps in Research

More research is required to understand the differences in evapotranspiration rates and water use of different tree species suitable for planting riparian and floodplain 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. This will help to plant the right species in the right place in the right way taking into consideration their water use and water resources in specific catchments.

It is uncertain how well river woodland tree species in Scotland with adapt to long term drought. This will be dependent on their ability to tolerate drought due to adaptative mechanisms (such as deep-penetrating roots and strong stomatal control) and the timing and frequency of droughts over time. Research has found that climate sensitivity and drought seasonality determine post-drought growth recovery of oak species (*Quercus petraea* and *Quercus robur*) in Europe (Bose *et al.*, 2021). Both species showed rapid recovery or even growth compensation after summer droughts but displayed slow recovery in response to spring droughts where none of the two species was able to fully recover the pre-drought growth-level over the three post-drought year. The results indicate that oaks which are considered resilient to extreme droughts also show vulnerability when droughts occur in spring especially at sites where long-term growth is not significantly correlated with climatic factors. Further research is required to understand if riparian and floodplain tree species can adapt to drought in Scotland.

Evidence indicates that planting of broadleaved woodland is likely to have a relatively minor impact on water yield and low flows, although there is a need to strengthen the evidence base in the UK and to include riparian and floodplain woodland. Further research is required to understand if increased retention of floodwaters by floodplain woodlands lead to enhanced low flows in Scotland. Data can be returned from the continuation of long-term trials.

There are hydrological models available which have been used to estimate woodland impacts on water resources but there are limitations to their application. For example, the parameter values used in the Hydrological Landuse Change (HYLUC) model have been restricted to a few broadleaved woodland tree species derived from a small number of sites in central and southern England (in Nisbet *et al.*, 2011). The Hydrological Simulation Model (Hysim), which is the main rainfall runoff model used by Scottish Water, includes parameters such as inception storage and rooting depth where outputs can be fed into water resource models (such as Aquator). Hydrological models such as Hysim can be potentially further developed to refine parameters using information from sites in Scotland, and test if for a wider range a wider range of tree species including river woodland types. Expert judgement is still required to tailor model outputs to specific site conditions.

A national-scale risk-based support tool to evaluate the vulnerability of water supplies (quantity, quality) to drought, including socio-economic and environmental drivers, to provide an evidence base to target investment and sustainable mitigation measures is required and is being developed in Scotland.

Further research is needed to understand the impact of floodplain woodlands on river flows. If natural floodplain woodlands have a much greater water use than the vegetation cover being replaced, large scale woodland restoration may not be suitable for catchments experiencing a shortage of supply in dry years (Kerr & Nisbet, 1996). Similarly, the planting of water demanding species would not be advisable in riparian woodland alongside stream which suffer from a cessation of low flows during dry periods. However, if the increased retention of floodwaters by floodplain woodlands led to enhanced low flows, this could help to compensate for the effect of higher evaporation losses on summer river flows (Kerr & Nisbet, 1996).

Agroforestry practices within the riparian zone has potential for drought adaptation due to trees role in moderating the microclimate although silvoarable agroforestry practice is rare in Scotland apart from where there is significant wind erosion of soils such as on the Moray coastline (Perks *et al.*, 2018). As drought conditions become more frequent, particularly on the East coast of Scotland, this practice could become more popular. Further research in the application of silvoarable agroforestry practice in Scotland is required to understand the right crops and tree species to use under Scottish conditions and under drought conditions and a changing water resource situation.

There is little understanding of how hydraulic lifting and bioirrigation processes would work in Europe, the UK and Scotland and thus no understanding of how to advise farmers on how to incorporate these processes into agroforestry designs in the UK. This is critical evidence to help feed into helping land managers weigh up changes in their land management practices.

3.3 Climate action – alleviating flood risk

3.3.1 Overview of benefit

This benefit focusses on the role of river woodlands in managing flood risk. This role is called natural flood management (NFM), as natural assets are used, for example, to slow the flow of water along pathways to rivers or store water close to the source of runoff. Riparian and floodplain woodlands are recognised as one of the woodland creation measures in SEPA's Natural Flood Management handbook[15]. Regarding natural flood management in the UK, most work has focused on smaller scale catchment or tributaries, and at least in the main stem riparian setting. When applied with due diligence and measured consideration, appropriately planted and managed woodlands (floodplain, cross-slope and riparian) can mitigate flood risk and delay flood peaks, both temporally and spatially (Cooper *et al.,* 2021).

Currently approximately 79,000 homes and 29,000 non-residential properties are at risk of flooding in Scotland. This, coupled with the pressure of population growth, is likely to result in increasing pressure on flood risk management in order to maintain current levels of protection. Projected climate change over the next century is expected to increase the frequency and severity of floods in Scotland. Modelling in uplift flow peaks predicts increasing flow peaks of roughly 50% on average for the 2080s (Kay *et al.*, 2019a). As climate change increases flooding events, it will also create more active channels and subsequently in some areas increase sediment delivery from the tributaries to the main stem. As sediment is mobilised in tributaries more frequently than the main channel (due to steeper gradients), this can result in increased aggregation in the main stem channel, reducing channel capacity and subsequently causing greater floodplain inundation (Lane *et al.*, 2007). River woodlands, however, can play a role in reducing sediment from the main stem and tributaries. By doing so they help maintain watercourse capacity and reduce flooding. Improvements in the condition of river woodlands across key tributaries in the catchment is key to creating resilient systems under different climate change scenarios.

The section focuses on the evidence which supports the role that riparian woodland, floodplain woodland, riparian woodland buffers and large woody material (including artificial leaky dams) play in contributing to reducing flood risk via two main functions of slowing the flow of water and reducing coarse sediment delivery and siltation of channels. It does not include catchment woodland or cross-

[15] More information on natural flood management is available here: sepa-natural-flood-management-handbook1.pdf

slope woodland evidence as not defined as river woodland types in this report (but further evidence on these types is included in Annex 3).

There is a large body of research which has been undertaken in the UK to develop a strong evidence base for the role of river woodlands in flood alleviation. The Environment Agency (EA) Report on Working with Natural Processes- Evidence Base is the key reference for this work (Burgess-Gamble *et al.*, 2018). It includes a comprehensive systematic literature review. A summary of the findings is provided in this section from the Evidence Base and supplemented by more recent research results and developments. The confidence rating of low, medium and high confidence in the science, based on the potential effectiveness of each measure, ranked by the scientific experts in the EA's technical report is also included (Ngai *et al.*, 2017).

Beneficiaries:

The beneficiaries of natural flood management including river woodland measures are downstream communities, businesses, land managers, water companies (Scottish Water) and the local authorities who manage flooding. These river wood measures can reduce the peak of the flood, and therefore the extent of flooding to people's homes and businesses. It can also give people more time to take emergency actions such as putting in place property flood barriers and moving to a safe place. If properties are at less risk of being damaged by flooding this potentially reduces insurance premiums, and insurance company payouts to repair properties. Natural flood management of water sources and pathways at a catchment scale is one of the options available to local authorities to manage flood risk, alongside engineered options. Riparian landowners and tenants will benefit from costs saved from less dredging of rivers to prevent local flooding by having natural woodland trapping sediment before reaching the channel bed[16] as well as Local Authorities if it is necessary as part of a Flood Protection Scheme.

3.3.2 Slowing the flow of flood water

Functional processes

Riparian and floodplain woodlands can slow floodwaters and increase water depth on the floodplain. Tree butts, surface roots, deadwood and leaf litter all contribute to a hydraulic roughness which exerts a barrier or drag effect on surface flows. Much is known about how floodplain woodland affects both floodplain and hydraulic roughness as well as the influence of the woodlands in diverting floodplain flows and driving the formation of multiple channels and backwater pools (Piégay & Bravard, 1996) (in Ngai *et al.*, 2017). Engineering tables show how dense, multi-stemmed woodland typical of natural floodplain woodland exerts the greatest hydraulic roughness of all vegetation types, with values of Manning's five times or more greater than those for grassland (Chow, 1959).

Brown (2013) showed how riparian trees can maintain high evaporation losses, creating potential additional below-ground water storage, especially in summer periods (in Ngai *et al.*, 2017). Above-ground water storage is increased by the friction/drag of riparian trees, which slows water flows and increases water levels, although this can be partly offset by enhanced channel velocities, depending on the presence of large woody material dams (Thomas and Nisbet, 2006) (in Ngai *et al.*, 2017).

[16] Based on the record of dredging and sediment removal applications received in SEPA (2015-2020), most sediment removal in Scotland is associated with registrations, removing sediment from previously straightened channels, in sections of rivers less than 500m within channels between 1-5m wide, or longer sections of natural channels, up to 1km long but from discrete areas of gravel bars. These registrations are normally associated with local management of floods associated with accumulation of silt/gravel in low energy channels. Riparian vegetation could play a role trapping sediment before reaching the river channel.

Large woody material is an integral part of naturally functioning riparian woodlands. Large woody material is known to exert a significant effect on channel flows and processes, as it affects channel development, sediment deposition, bank scour and overbank flows. There is evidence in the UK related to engineered wood structures, where leaky barriers are created and anchored in specific locations along a river (Ngai *et al.*, 2017). Leaky barriers can reduce flood risk by slowing the flow of water in a stream and causing the water to flow over the bank to use floodplain storage. Over-bank flows restore the river-floodplain connectivity which can reduce flood peaks, slow water velocities and attenuate flow by storing water on the floodplain (Dadson *et al.*, 2017). This can cause local flooding, but the water stored decreases flood risk downstream.

During floods, wood can be mobilised and deposited at natural or artificial entrapment points in the channel (see Dadson *et al.*, 2017). More wood in the system can lead to less wood travelling downstream. Blockage of bridges, trash racks and culverts with large wood can cause flooding upstream of the blockage. This risk though can be managed with good infrastructure with the correct design of bridges and culverts. CIRIA has developed a NFM design manual which includes large woody material (Wren *et al.* 2022). Implementing leaky barriers together with other NFM measures require hydrological and catchment planning. If leaky barriers are engineered and placed incorrectly in a catchment, they could potentially contribute to flood synchronisation issues *(*Ngai *et al.,* 2017*)* as found with other NFM measures.

Leaky dams in the Eddleston catchment, Scotland. Credit: Tweed Forum.

There is evidence to show that the effect of Integrated Buffer Zones (IBZs) (involving a ditch pond and an infiltration zone planted with alder or willow) on managing surface water runoff provides localised benefits to flooding if strategically located. Results from IBZ at the Balruddery Research Farm in Angus showed that these features can, delay inflowing tile drainage water and also assist in storing part of the surface runoff from adjacent fields, especially if the IBZ is optimized for this requirement via an outlet flow control (Zak *et al.*, 2019). Empirical field observations have demonstrated that riparian tree-based buffer strips can provide runoff attenuation (Mason-McLean, 2020).

Measured effect

Evidence from observations at the reach scale plus modelling studies has shown that riparian woodland has the potential to reduce small to medium flood flows in small and medium sized catchments (Ngai *et al*; 2017). Modelled data has provided the best source of evidence that riparian woodland (as a standalone measure) can reduce flood flows at the catchment scale. Modelling studies provide a range of results, with most predicting that riparian woodland can reduce flood peaks by 2–8% for events smaller than 1% AEP (Ngai *et al.*, 2017). Floodplain woodlands can help reduce flood peaks (0-6%), delay peak timing (2 hours or more), desynchronise flood peak and reduce peak height based on a review of studies (Ngai *et al.*, 2017).

Dixon *et al.* (2016) applied a spatially distributed flood model (OVERFLOW) to analyse the effects of river restoration and woodland creation on flood flows within the 98km^2 catchment of the Lymington River in southern England. They found that the restoration of riparian woodland along 20–40% of the total catchment area was the most effective of the NFM measures tested, reducing peak flows by up to 19% for a 3% Annual Exceedance Probability[17] (AEP) flood. The magnitude of effect is greater if the woodland is appropriately placed to maximise the desynchronization of a sub-catchment contribution to the downstream flood peak.

Numerous studies have modelled naturally occurring wood in rivers. For example, Dixon (2013) found that naturally occurring log jams account for 65% of flow resistance in forested river channels; this rose to 75–98% where the log jam was inducing a distinct step in the water profile. However, when modelling log jams alone, Dixon (2013) found a variable response with less clear spatial trends than for forest restoration, and also noted issues with synchronisation of flood peaks. Modelling work by Kitts (2010) found that large woody material (constructed woody debris dams) in a medium sized catchment (12 km^2) slowed a small flood peak by up to 33%.

An empirical study, found a significant deceleration in flood wave propagation over a 282 m reach of channel with large woody material in a 1 km^2 catchment, causing a 3-minute delay in the flood peak for a small flood event (with a return period of 3.5 years) (Wenzel *et al.*, 2014).

The effectiveness of natural flood management measures involving riparian woodland planting and large woody material dams has been called into question due to the lack of empirical studies and results from Before-After-Control-Impact (BACI) designs assessing impacts at a range of catchment and flood event scales. However, the Eddleston Water catchment study in Scotland, with 13 stream gauges operated continuously over nine years, is based on both longitudinal and comparison data sets (Black *et al.*, 2021). Two years of baseline monitoring was followed by seven years of further monitoring after a range of NFM interventions across the 69 km^2 catchment. The study examined changes in lag as an index of hydrological response which avoids dependence on potentially significant uncertainties in flow data. Headwater catchments up to 26 km^2 showed significant delays in lag of 2.6–7.3 hr in catchments provided with leaky wood structures, on-line ponds and riparian planting, while larger catchments (up to 64.4 km^2) downstream and those treated with riparian planting alone did not; two control catchments failed to show any such changes. Results showed an increase in lag times with increasing flow for the smaller Eddleston catchments suggesting that the NFM measures have increasingly large impacts on lag times as the scale of event increases closer to bankfull discharges (Black *et al.*, 2021). This may be due to the design of the NFM measures, where, for example, leaky wood structures, are very "leaky" at lower flows (lower than bankfull discharge) but begin to attenuate flows close to bankfull discharge and then push water on to the floodplain in these catchments. This may be due to their ability to make use of "expandable field storage" (Hankin *et al.*, 2020; Kay *et al.*, 2019b). This raises the possibility of NFM effectiveness at higher event magnitudes, contrary to the Dadson *et al.* (2017) review: "the larger the catchment and the larger the flood, the smaller is the scope for slowing the flood or storing the floodwater to reduce the flood hazard", though it is not possible to predict the maximum extent of this effectiveness from this analysis (Black *et al.*, 2021).

[17] The Annual Exceedance Probability is the chance or probability of a natural flood event occurring annually and is usually expressed as a percentage.

The empirical evidence due to riparian and wetland tree planting in the lower catchments in the Eddleston catchment is unclear and it is also suggested this is due to the immaturity of the trees, or other complicating factors (Black *et al.*, 2021). Monitoring the leaky dams in the Eddleston (Middle burn sub-catchment) showed a 15% reduction in the flood peak discharge where there was 3,000m^3 of attenuation storage within the Middle Burn sub-catchment (Barnes, 2018).

Application of 1D and 2D hydraulic models to a 2.2km reach of the River Cary in Somerset demonstrates that the planting of floodplain woodland could have a marked effect on flood flows (Thomas & Nisbet, 2007). The additional roughness created by a complete cover of woodland along the right bank of the floodplain increased flood water storage by 71% and delayed the downstream progression of the flood peak by 140 min. A smaller 50 ha central block of woodland that spanned the full width of the floodplain had less of an effect but was still significant in storing 15% more flood water and delaying the flood peak travel time by 30 minutes. This caused a backwater effect that extended 300 – 400 m upstream of the woodland. Despite uncertainty in the modelled outputs, these findings suggest that there is considerable scope for using floodplain woodland as an aid to flood control. The scale of the modelled woodland was very small in relation to the size of the catchment, implying that a larger woodland block or a series of similar-sized ones could exert a much greater downstream impact. The subsequent planting of 7.5 ha of riparian and wetland tree planting in 6.89km^2 of the School catchment in 2013 has shown no evidence of any significant increase in lag time from field data results. However, as this is a large proportion of the catchment area compared to the Thomas and Nisbet (2007) modelling results, the lack of significant effect may be due to local factors such as the relative immaturity of the trees (in Black *et al.*, 2021).

Short rotation coppice (SRC) planted in the floodplain could also help with slowing the flow on floodplains. Modelled work by Rose and Rosolova (2015) found that planting short rotation willow across the floodplain could, for a 1% AEP flood, increase floodplain flood depth >20cm and velocities by >40%. The plantation acted like a 'green leaky dam', holding back and reducing the speed of floodwater propagation. This created a backwater effect that extended up to 300m upstream of the woodland. (See section 3.11. for information on the provision of biomass for energy from river woodlands).

Riparian buffer strips can attenuate flow peaks. Mason-McLean, (2020), modelled different scenarios of grass-based buffers and riparian woodland buffers, the 50 m riparian woodland buffer strip scenario was highlighted to be the most effective width and vegetation type, reducing flow peaks at all spatial scales on average by ~9%. This was evident at 1-in-2 year for the upper catchment, and QMED[18] for the middle and lower catchment.

Factors influencing effectiveness

Important catchment factors affecting the performance of riparian woodland to slow flows include slope, channel gradient and floodplain width which influence the speed, volume and space for floodwater, as well as the degree of connection with riparian woodland (Ngai *et al.*, 2017). Lower gradients and wider floodplains tend to enhance the interaction between the woodland and flood flows, slowing response times and increasing flood storage. Such conditions are also more conducive to the formation and action of large woody material dams.

The effectiveness of an approach depends on its location in a catchment as the effect on flow pathways and timescale of water retention are spatially variable. The effectiveness of a measure also

[18] QMED: At a gauged location, it is the median of the Annual Maximum (Amax) flood series. It is approximately equivalent to bankfull flow in Scottish rivers.

depends on its maturity (Wilkinson *et al.* 2019). For example, whilst a leaky barrier is effective the moment it is created, planted trees take time to establish therefore their temporal effectiveness generally increases over time, for instance, ability to intercept rainfall (depending on species and landscape in which it is located), generally increases with maturity (Stratford *et al*., 2017)

The relative location or placement of riparian woodland within a catchment can have an influence on the magnitude of the effect on peak flows by synchronising or desynchronising sub-catchment flow responses. For example, modelling work by Odoni and Lane (2010) found that riparian planting within the lower reaches of the Pickering Beck catchment would increase peak flows by delaying the evacuation of waters to bring them into phase with those draining the upper catchment (Ngai *et al*., 2017). Planting in the upper catchment delivered the greatest benefit, by spreading out the flow response and thus lowering the overall flood peak. Targeting the middle reaches produced a neutral or beneficial effect. Similar findings were obtained by Dixon *et al*. (2016), who observed that the largest reductions in peak flows resulted from placements designed to maximise the desynchronisation of the timings of sub-catchment flood waves, which typically involved areas in the middle and upper catchment (Ngai *et a*l., 2017).

The design and management of riparian and floodplain woodland influences its effectiveness in slowing flows and is summarised well by Ngai *et al*., (2017) (Annex 2). The most important factors for riparian woodland are length, width, structure, tree spacing, species mix, amounts of deadwood and management regime. The key factors influencing the effectiveness of floodplain woodland to reduce flood flows includes the extent and placement of floodplain woodland, as well as its shape, alignment and structure.

The effectiveness of leaky dams and large wood structures can be improved using effectiveness numerical modelling (Addy & Wilkinson, 2019b) as part of the design. The design of tree-based buffers influences its effectiveness in runoff attenuation, for example with complimentary measures when located on a hillslope (Mason-McLean, 2020).

When designing floodplain woodlands there are several additional effects on natural processes associated with geomorphic changes that can be considered to improve effectiveness, e.g., channel widening and formation of floodplain channels (Wen Lo *et al.,* 2021), that can have further implications in flood attenuation by slowing down flows and increasing storage capacity.

3.3.3 Reducing coarse sediment delivery and siltation of channels

Functional processes

There is a very strong understanding of the natural hydromorphological processes which are involved in reducing coarse sediment delivery and siltation of channels by riparian vegetation which helps to maintain watercourse capacity and reduce flooding (Gonzalez del Tánago *et al*., 2021). Riparian woodlands can reduce sediment from the main stem and tributaries by adjusting natural rates of erosion on the banks, controlling sediment supply in-channel (log jams) and reducing water energy by increasing bank roughness. Also, engineered log jams (ELJs) are employed to address river restoration goals and a range of river management problems including coarse sediment movement that could impact flood events, for example in the Bowmont Water in the Scottish Borders (Addy & Wilkinson, 2016). Floodplain woodlands can increase floodplain connectivity and support the creation of functional secondary channels across the floodplain to convey water and sediment, allowing coarse sediment deposition and trapping fine sediment beyond the main channel (Hughes, 2003; Gonzalez del Tánago *et al.*, 2021). By slowing water flows, floodplain woodland is effective at enhancing sediment deposition on the floodplain, reducing downstream siltation within river channels (Piégay and Bravard 1996; Jeffries & Sears, 2003). Large woody material associated with riparian and floodplain woodland will reinforce their capacity to retain sediments (Gonzalez del Tánago *et al*., 2021).

Measured effect

In the New Forest, southern England, Jeffries & Sear (2003) report that, during flood events, the amount (0–28 kg m^{-2}) and pattern of sediment deposition were both greater and more variable on areas of forested floodplain of the Highland Water than on the non-forested floodplain. The highly variable pattern of accretion can be explained by the combined effects of topography and organic material present on the surface of the floodplain.

In Scotland, assessment of log jam structures in response to flood events in the Bowmont Water, in the Scottish Borders, is contributing to design developments (Addy & Wilkinson, 2016). In the Bowmont study, the log jam placement goal of increasing sediment storage was not fully met. There was evidence that structures trapped sediment but evidence to show a reduction in sediment load in the waterway was limited and not fully monitored. Longer term monitoring is thus required to understand the impact of leaky barriers on reductions of sediment loads in waterways and flooding. Further work is developing in Scotland in understanding the risks of leaky barriers, to minimise these risks and for strategic placement. This involves a risk matrix framework developed by SEPA.

The Logie Burn is a headwater stream with a sand-gravel stream bed in north-east Scotland. It was restored by reconnecting its pre-modification channel to improve the sediment transport process and subsequently increase habitat diversity and complexity. Morphological, sedimentary and retention (wood, phosphorous and organic matter) responses were monitored over three years (Addy & Wilkinson, 2019a). Total wood load increased in the restored reach over the three years including a large tree that collapsed into the channel causing a morphological change. The fallen tree blocked 72% of the channel as an underflow log jam. In the course of a year, the log jam trapped 5.4 m^3 of sediment and initiated the erosion of 19.5 m^3 of sediment by directing erosive currents towards the bank (leading to local channel widening). At the reach scale, the accumulation of in-channel large woody material did not lead to an increase in physical channel complexity. There was no evidence of reduced sediment load in the waterway and in the short term (1 year), the log jam formation caused a net increase in sediment erosion. However, these results are short term results, and it is important that they are placed in context especially in relation to timescales as the effects will evolve over time.

In a single study in the Upper Wharfe catchment in the Yorkshire Dales National Park, modelling work has shown an 80% reduction in coarse sediment loading from strategically planting 5.2% of the catchment in areas of high risk of slope failure and along source flow pathways (Lane *et al.*, 2008). The results indicate that it is possible to achieve significant reductions in sediment yield through source control using woodland measures.

Factors influencing effectiveness of measures

The design of log jam and large wood structures will affect the effectiveness to store sediment. The management of naturally occurring in-channel large wood and its artificial addition provide a useful approach to retain sediment. Numerical modelling can support the design of effective wood structures guiding its placement and size to retain and distribute sediment in the channel and support the management of naturally occurring in-channel wood (Addy & Wilkinson, 2019b). The design of structures can also identify wider benefits for fish species, the physical characteristics of a woody placement that have the potential to affect fish include space underneath the structure, structure height, and sizes of the gaps within the structure (Dodd *et al.* 2016).

Geomorphological effects of in-stream wood structures can impact effectiveness of sediment retention and deposition beyond the structure, for example widening the channel can increase sediment retention in the long-term but increase sediment load from bank erosion in the short-term.

Strategic planting by identifying erosive banks and areas in the catchment of high risk of slope failure and along source flow pathways will make sediment retention more effective.

3.3.4 Evaluation of evidence

Strength of evidence (based on quality of studies)

Slowing the flow: The evidence is **moderate** for riparian woodland, floodplain woodland and large woody material. There has been a comprehensive review of evidence for riparian woodland and woody material, the evidence is currently based on some empirical studies and observational statistical studies. There are also projections made from models with some data input to determine parameters. Modelling is starting to incorporate physical processes. For floodplain woodlands the evidence is mainly from flood models and more observational data is required to verify findings (Ngai *et al.*, 2017). Also, there is a need to dis-entangle the effect of each of the measures, modelling studies generally look at all these measures as a collective. There is empirical evidence, backed up with Before-After-Control-Impact (BACI) design, that riparian woodlands, in combination with leaky woody structures and on-line ponds, slow floods significantly in the headwaters of small catchments in Scotland.

Reducing coarse sediment delivery and siltation of channels: The biophysical processes underpinning river woodland measures to reduce sediment and siltation are well known but there is less empirical data to measure effect, so the evidence is **moderate**. Log jam structures can trap sediment (if designed for that purpose) but there is no evidence to show a reduction in sediment loads yet from short term studies. Reductions in sediment loading from strategic planting in upland catchments show a strong positive impact but this is based on modelling work.

Confidence rating for effectiveness

Slowing the flow: Science experts conclude a medium level of confidence of riparian woodland being effective at the local scale but low confidence across a range of scales (Ngai *et al.*, 2017).
Science experts conclude a medium level of confidence of floodplain woodland being effective at the local scale - at the middle and lower river reaches of moderate to large catchments. A low level of confidence is assigned to understanding these effects at catchment scale. Observed and modelled evidence shows that large woody material forming leaky barriers are effective at reducing flood risk at a local scale for small flood events (Medium confidence) (Ngai *et al.*, 2017). However, there is limited evidence of their flood risk effect for large events at greater catchment scales.

Reducing coarse sediment delivery and siltation of channels: there is a high level of confidence in the effectiveness of large wood structures and leaky dams retaining sediment, trapping fine sediment, encourage sediment sorting, reduce sediment transport, help create pool, riffle and bar formation (Ngai *et al.*, 2017).

Limitations & Gaps in Research

In large catchments, the efficacy of riparian woodland creation on flood risk is limited by the relatively small footprint and reduced interaction between the riparian zone and river flow as channel width increases.

Riparian woodland is considered unlikely to reduce large and especially extreme floods, probably regardless of catchment size, due to its relatively small extent/area. Results from the Eddleston catchment in Scotland show a significant reduction in lag period in the small headwater catchments from a combination of NFM measures including riparian woodland but results from other catchments remain inconclusive because the planted trees are too young to be expected to generate any significant effect and any detailed analysis awaits the collection of longer-term data. While the Eddleston study found increasing effect with flood magnitude, it is likely that for extreme events, there is unlikely to be an effect.

The EA Evidence Base (Burgess-Gamble *et al.*, 2018) concludes that there is still a need to better understand how the type of woodland, its placement in the catchment and the catchment size affects the flood risk impact. Better model parameters are required to represent woodland hydrological processes to assess their flood risk impacts and to test the upscaling of these to the catchment level. A model which incorporates canopy characteristics with streamflow response at varying temporal and spatial scales and can be adapted to account for the different types of woodland (including riparian and floodplain) cover found in "real world" scenarios would be very beneficial in guiding planning of afforestation (Cooper *et al.* 2021).

Further work in Scotland is required to understand the impact of planting trees on reducing sediment loading in rivers. This Includes the application of models like SEDMAP which determines failure likelihood (slope stability) without and with a soil and root cohesion treatment. Sediment fingerprinting and SCIMAP (SCIMAP -Diffuse Pollution Risk Mapping) are useful tools which could be used in combination with each other and in combination with opportunity mapping to help build an evidence base. In Scotland, the ST:REAM model was produced to identify river reaches with potential for coarse sediment deposition, transport and erosion that could help mitigate flood risk (Parker *et al.*, 2012; Parker *et al.*, 2014; Martinez-Romero, 2013; Clifford *et al.*, 2015), but this work lacks sediment supply inputs. Further work is being undertaken to identify coarse sediment sources in Scotland and create a map of coarse sediment sources (PhD lead by Edinburgh University supported by SEPA, Anya Towers) that can support previous and new work.

Further data from Scotland on quantifying the role of large woody material in reducing soil erosion, sediment retention and reducing sediment losses to watercourses. This data could be obtained from long term monitoring at existing research trial sites, such as the Logie Burn in the River Dee catchment (Addy & Wilkinson, 2019a).

Further work is required on improving how models represent floodplain woodland processes. For example, more floodplain roughness data is required to calibrate flood models. No measured data appear to be available at the catchment scale quantifying the impact of floodplain woodland on flood peaks. Instead, measurements have focused on interactions between woodland, water flows and sediment at the reach level or on modelling these processes and upscaling the effects to the catchment level.

Further developments in the design and construction of the large woody barriers are required. More research is needed to better understand the impact of leaky dams during larger flood events across a range of spatial scales (Ngai *et al.*, 2017).

3.4 Climate action: carbon

3.4.1 Overview of benefit

Forests and woodlands, including river woodlands, are a key component of the global carbon cycle, and their effective management is an important mechanism for reducing atmospheric greenhouse gas (GHG) concentrations (Morison *et al.*, 2012). Global greenhouse gas emissions need to reach net zero by 2050 to have a reasonable chance of limiting warming by 1.5C (IPCC, 2018) otherwise there will be irreversible impacts to life on earth. To reach this target, in the UK, unprecedented transitions in all aspects of society are required including a fall of 64% of emissions from land-use (CCC, 2020). Trees and woodlands absorb carbon, which could deliver half of this reduction (CCC, 2020). Net zero emissions of all greenhouse gases by 2045 is a legislative target in Scotland and this goal is being widely adopted across government, businesses and society. The impacts of climate change include risks to food security, human health, safety and security, risks to our natural environment including terrestrial, freshwater, coastal and marine species, forests and agriculture and damage to our infrastructure, transport and communication links from extreme temperatures, storms, flooding and coastal erosion (CCRA3).

The climate crisis is simpler to communicate to the public in clear, memorable terms that capture public attention, in comparison to biodiversity (House of Commons Parliamentary Debate, Restoring nature and climate change, 28th October, 2019). It is increasingly recognised, however, that tackling climate change and biodiversity loss are two sides of the same coin.

This section identifies the evidence for river woodlands contributing to action to combat climate change through the main functions of sequestering and storing carbon.

Beneficiaries

Changes in climate affect communities and enterprises in both rural and urban areas. Climate change mitigation will be of benefit to all industries including manufacturing, agriculture, forestry, energy, water, transport and Information and Communication Technologies. Many businesses as well as government are adopting net zero carbon targets. Actions include reducing emissions as a priority and offsetting carbon emissions where river woodland planting has a role to play in the right locations. The Woodland Carbon Code provides a verified standard for woodland projects for the voluntary carbon market in the UK[19] and attracts additional private finance to secure the associated carbon savings.

3.4.2 Carbon sequestration and storage

Functional processes

The main processes in which trees can mitigate climate change include carbon sequestration[20] and carbon storage and are generally well understood (Read *et al*., 2009; Morison *et al*., 2012; Pan *et al*., 2013). Trees and other woody vegetation sequester carbon when they grow, reducing the amount of carbon dioxide in the atmosphere and storing carbon in tree biomass and forest soils adding to the overall carbon stock[21]. Mycorrhizal fungi in the soils and roots of the tree support tree establishment and growth. Its role as a soil carbon store is also well understood (Anthony *et al*., 2022, Tedersoo *et al.,* 2009, Ouimette *et al*., 2020). Trees can also increase the carbon in any soil type through above ground and below ground litter production.

Not all carbon is stored. There is a carbon cycle with decomposition through microbial action. Carbon is also released back into the atmosphere or water when trees are burned or decompose, Carbon release rates will differ for example burning is a rapid process and decomposition will be slower with rates differing depending on tree species and other environmental factors. Native riparian woodland left to grow to maturity and managed predominately for conservation allows carbon to be stored for a long time and for carbon to build up in the soils. If trees are felled as a part of the management of a

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[19] Home - UK Woodland Carbon Code

[20] Carbon sequestration: is said to have occurred if C is removed from the atmosphere and adds to C stock within one or more reservoirs (trees, soil etc) (Morison *et al*., 2012).

[21] Carbon stock: the amount of carbon in the system or its components at a given time. Either expressed as mass per unit land area (e.g. tC ha^{-1}), or as a mass for a defined area (e.g. MtC) (Morison *et al*., 2012).

type of river woodland, the length of time in which the carbon is locked up in timber and other products will depend on the after use of the timber or product.

There is evidence from the international literature which suggests that river woodlands would play a substantial role in carbon storage in Scotland. The global review by Sutfin *et al.*, (2016) explain how natural river systems with riparian and floodplain woodland ecosystems store a substantial amount of carbon. The largest and most persistent reservoirs of carbon include:

i/ standing riparian biomass (e.g.: standing trees on the banks),
ii/ large, downed wood (e.g.: large woody material in stream) and
iii/ floodplain sediment and organic matter (beneath the surface as litter, humus and soil organic carbon).

The size of each of these carbon stores will vary with scale, ecology, geology and climate. They propose that broad valleys with complex channels and wet conditions in cool regions such as found in Scotland are optimal conditions for organic carbon retention. The biophysical processes in which riparian woodland store soil carbon is understood and explained in section 3.6.2.

Measured effect

When reviewing the effects of woodland expansion on ecosystem services (ES), the largest number of studies of regulating and maintenance ES relate to the regulation of the chemical composition of the atmosphere through carbon sequestration and storage (Burton *et al.*, 2018).

There are few direct measurements of carbon uptake by woodlands (e.g. with canopy-atmosphere flux experiments), being limited in the UK to two broadleaf woodlands (Thomas *et al.* 2011; Wilkinson *et al.*, 2012) and two conifer plantations (Clement *et al.* 2012; Xenakis *et al.* 2021). There are also similar measurements from Ireland for Sitka spruce (e.g. Saunders *et al.*, 2014) and in NW Europe. However, none of these are river woodlands, as the direct stand-scale measurement approach requires extensive areas of woodland in order to determine carbon uptake rates and is not suited to more linear features.

Most evidence is based on model predictions where various national scale models predict that afforestation can sequester significant amounts of carbon, including broadleaf and native woodland types (Perks *et al.*, 2010; Sozanska-Stanton *et al.*, 2016, Matthews, 2020) but this does depend on the previous land-use and soils at individual sites (Mayer *et al.*, 2020).

Perks *et al.*, (2010) presents estimated net carbon sequestration potentials for the Scottish Forest Alliance (SFA) new native woodland creation sites (planting 6468ha in total) using a bespoke empirical forest carbon model. The mean carbon sequestration potential was estimated to be 53.9 tC ha^{-1} (equivalent to 197.7t t CO2eq ha^{-1}) over the first 100 years of the project. The average carbon sequestration potential per year from native woodland creation was estimated to be 0.54 tC ha^{-1} y^{-1}.

The ECOSSE model applied at a national scale in Scotland simulates soil carbon (C) and nitrogen (N) dynamics in both mineral and organic soils using climate, land use, land management and soil data, and simulates changes in soil organic carbon (SOC) and soil N_2O and CH_4 emissions (Matthews, 2020). ECOSSE was used in the work by Matthews *et al.*, (2020) to model the change in soil carbon stocks for different afforestation options including non-managed forest nature reserve and close-to-nature forestry as well as combined objective forestry, intensive even-aged forestry and wood biomass production with different management options including preserving natural processes without human intervention, delivering multiple benefits to maximizing biomass production or revenue from timber. The calculations assessed how much area was available and suitable for the different afforestation options, and what carbon sequestration could result for five periods (20, 40, 60, 80 and 100 years).

The Native Broadleaves option covers an extensive potential area but close to half of the area would result in a net depletion of carbon stocks. For cropping, grasslands and semi-natural antecedent land uses on lower carbon content soils, there are no further gains beyond 60 years and in some cases a small decline in net carbon. For higher organic content soils, the rate of loss declines steadily over the period but for some is still substantial even after 100 years, even with no further management disturbance. Recommendations from this ECOSSE application in Scotland (Matthews, *et al*., 2020), were that new upland native broadleaf afforestation (which would include riparian woodlands in the uplands) should be promoted through natural regeneration or low impact cultivation, which minimises soil disturbance losses and is managed long-term as a carbon reserve. Even with this management regime, carbon accrual will be slow due to the low yield of native broadleaves on poor soils in upland sites. Productive broadleaves on better soils can, however, deliver net carbon sequestration early in their rotation and can be integrated into farmland management, using otherwise lightly utilised land or as shelterbelts or agroforestry which is relevant on a landscape scale.

Evidence on carbon sequestration and carbon storage for native woodland in Scotland are largely based on models (e.g.: Perks *et al*., 2010; Răzauskaitė *et al*., 2020). There are several global and regional analysis done on analysing forest soil carbon stocks and under different land-use change scenarios (as described in Mayer *et al*., 2020). However, actual measurements on grown trees from the effect of afforestation on soil organic carbon (SOC) is dominated by chronosequence studies of Sitka spruce plantations (in Burton *et al*., 2018). A future source of information will be the Scottish Forest Alliance (SFA) native woodland sites which were established to collect data on changes in carbon as the woodlands mature, in the vegetation and soil (Perks *et al*., 2010). This included the establishment of an evidence-based carbon baseline for the SFA sites and involved vegetation, root and soil sampling with the development of a robust site sampling strategy at Glen Quey. The project includes three river woodland types: Ash-alder woodland, Aspen-birch, and waterlogged 'boggy' areas of Willow-birch. The data collected will be used in the development of improved empirical forest carbon models, which currently predict that afforestation can sequester significant amounts of carbon in broadleaf or native woodland in Scotland (Perks *et al*., 2010). These models also underpin the carbon sequestration calculation tool (which includes carbon stored in soils), used in the UK Woodland Carbon Code.

The global review by Sutfin e*t al*., (2016) describes quantified values for carbon stocks in temperate regions for riparian and floodplain woodlands to include standing riparian biomass, large dead wood and sub-surface sediment (humus and soil) and organic matter. Highest values for total standing riparian biomass Organic Carbon (OC) pools (including vegetation and large wood were observed for mesic old growth, conifer-dominated riparian forests in the southern Rocky Mountains while lowest values occurred in early successional cottonwood stands, herbaceous-dominated meadows and willow shrub stands (in Sutfin *et al*., 2016). At disturbed temperate sites, alteration or removal of riparian vegetation resulted in lower riparian biomass OC pools. Mature temperate hardwood forests include a wide diversity of tree and understorey species, yet total OC storage in riparian biomass ranges from ~100 to 300 Mg C Ha^{-1}. Volumes of in-stream wood tended to be greatest in temperate environments which have larger trees and longer decay rates. In the old growth, conifer-dominated riparian forests of the southern Rocky Mountains, standing trees account for only 7-22% of the total stored OC whereas down wood accounts for 77 to 93%. Sutfin *et al*., (2016) describes how data on litter fall rates is limited to warm, temperate forest floodplains in North America. Although soils are known to be the third largest reservoir in the global carbon cycle and store more carbon than living biomass and the atmosphere combined, quantified data on soil organic carbon (SOC) in river systems is limited. Modelling work taking into consideration both riparian biomass and soil carbon data from global reviews, predicted that, on average, globally, the establishment of riparian forest will more than triple the baseline of unforested soil carbon stock (Dybala *et al*., 2018).

Factors influencing effectiveness

The amount of carbon stored in a river woodland system will depend on tree species and age, the type of soils and the amount of disturbance. The global review by Mayer *et al* (2020) describes how stocks and accumulation rates of soil C differ under different tree species, with coniferous species accumulating more C in the forest floor and broadleaved species tending to store more C in the mineral soil. There is some evidence that increased tree species diversity could positively affect soil C stocks in temperate regions, but tree species identity, particularly N-fixing species (such as Alder which is a riparian woodland species), seems to have a stronger impact on soil C stocks than tree species diversity. Management of stand density and thinning have small effects on forest soil C stocks. In forests with high populations of ungulate herbivores, reduction in herbivory levels can increase soil C stocks.

The amount of organic carbon stored on the floodplain and in the channel as wood, varies with drainage area, forest stand characteristics (species composition and stand age), valley and channel characteristics (Sutfin *et al.*, 2016). Factors influencing the volume and resident time of stored wood in river systems include riparian forest stand age, stem density, species, woody decay rate, hydroclimatic disturbance and floods and wood recruitment mechanisms which includes individual tree topple, disturbance related mortality, bank and flood plain erosion and transport from adjacent uplands and channels (Sutfin *et al.*, 2016).

When estimating net carbon uptake for areas it is critical to take land use and soils prior to planting into account (Matthews *et al.*, 2020). Even over the long term (50-80 years) native woodland planted on semi-natural areas with soils rich in organic matter such as peatlands can continue to emit carbon for decades. In these locations the goal to mitigate carbon emissions then needs to be weighed up against other objectives. Whereas on areas that were previously grassland and cropping there is more likely to be a net gain in carbon. Modelling undertaken by Matthews *et al.* (2020), has produced maps for Scotland that could be used to help prioritise areas for carbon mitigation.

3.4.3 Evaluation of evidence

Strength of evidence (quality of studies)

Carbon sequestration & carbon storage: the biophysical processes that underpin the ability of trees and woodlands in general, to contribute to climate change mitigation via carbon sequestration and storage are well known. Evidence for the effect of afforestation on carbon sequestration is dominated by modelling work and is **strong** based on studies done. Further empirical field data on carbon is being collected for native woodland sites including river woodlands in Scotland to strengthen carbon sequestration calculations.

Limitations and Gaps in Research

The empirical evidence on carbon storage in river systems is predominately from the American literature and further data is required to understand differences in carbon storage on different types of river systems in Scotland. The Scottish Forest Alliance project will contribute to understanding the changes in carbon stocks in vegetation and soils over time on sites which include new riparian and floodplain woodlands. The Woodland Carbon Code carbon assessment protocol estimates biomass contributions from broadleaves species including riparian tree species based on crown biomass for oak and root biomass estimation for red alder (Jenkins *et al.*, 2018). Carbon estimations also assume that dead wood, litter and soil elements will not change significantly from the baseline [22]. The Woodland Carbon Code uses Natural England's report on carbon sequestration by habitats to derive

[22] 3.1 Carbon baseline - UK Woodland Carbon Code

non-woody biomass estimates, which is based on a review of current scientific literature (Gregg *et al.*, 2021). As improved empirical evidence from Scottish riparian and floodplain woodlands is gathered these predictions can be improved as part of guidance within the code.

There have been studies which consider non-carbon Greenhouse Gas (GHG) emissions from forestry in general (Morison *et al.*, 2012) and there are a number of studies for changing land-use involving woodland creation (Burton *et al.*, 2018). The ECOSSE modelling found that simulated Nitrous oxide and methane emissions under different afforestation scenarios for Scotland were negligible compared to the change in soil organic carbon (Matthews, 2020). However, studies that look specifically at non-GHG emissions for river woodlands and soil types are limited. This is an important field of research to maximise GHG mitigation measures and to plant 'the right trees in the right places' to meet the UK's net-zero targets by 2050 (CCC, 2020). It has been hypothesised that in flooded or waterlogged forests, trees may form a pathway for methane (CH4) produced in the soil to be emitted (Morison *et al.*, 2012). Results from one study in Scotland exploring soil carbon and methane flux dynamics from Scots pine peat bog woodland found that soil CO2 fluxes were significantly higher in the vicinity of the trees and lower in soil CH4 flux compared to the open bog (Mazzola *et al.*, 2022). It is suggested that the trees on bog edge woodland affect soil C fluxes in their proximity primarily due to the contribution of root respiration, but also as a result of their effects on soil moisture, enhancing soil CO_2 emissions, while reducing the CH_4 fluxes. The work concludes that there is still uncertainty about the complete greenhouse gas assessment, and further research would be needed in order to include the quantification of soil nitrous oxide (N_2O) dynamics together with the analysis of complete gas exchanges at the tree-atmosphere level.

3.5 Clean air

3.5.1 Overview of benefit

Trees can play an important role in influencing urban air quality and in mediating some of the negative effects of pollutants. Low to medium stature trees[23] which include many riparian woodland species can capture air pollutants and are particularly beneficial in an urban setting where space can be limited. Smaller trees are also less exposed to the wind and potential storm damage. With the appropriate design, riparian woodland networks running through towns and cities have the potential to provide huge co-benefits buffering air pollution from vehicles on roads which run parallel to popular riparian urban spaces, frequently used for recreation, health and active travel.

In the atmosphere of urban environments, the common air pollutants which are influenced by the presence of trees include the chemical pollutants of ozone (O_3), oxides of nitrogen (NOx), carbon monoxide (CO) ammonia (NH_3) and sulphur dioxide (SO2) and particulate matter consisting of tiny particles ($PM_{2.5}$ and PM_{10}) associated with the burning of fossil fuels in vehicles, power plants and various industrial processes. The air quality in Scotland is generally better now than it has been at any time since the Industrial Revolution due to reductions in emissions and improved pollution control. Despite these improvements, however, Scotland still has areas of poor air quality (CCRA, 2017), particularly in urban environments as a result of transport fumes. Climate change has the potential to exacerbate poor air quality. For example, during heat waves, air becomes more stagnant, and traps emitted pollutants, often resulting in increases in surface ozone. The main health-related hazard is particulates ($PM_{2.5}$ and PM_{10}), although ground level ozone also affects health and is the dominant hazard when considering future climate change impacts on air quality. As trees can remove

[23] large stature tree species are defined as a species in which a healthy, isolated 20-year-old specimen growing in good soil conditions typically attains a height of greater than 12 m and small and medium stature tree species are defined as species in which a healthy, isolated 20-year-old specimen growing in good soil conditions typically attains a height of (small) less than 6 m or (medium) between 6 and 12 m It is the species that is defined for stature and not the tree, and that this definition is also independent of age (Hand *et al.*, 2019a,b).

atmospheric carbon dioxide (CO_2) and reduce the impacts of pollutants such as PM_{10}, they are an important measure to consider in tackling air pollution in our towns and cities.

This section focuses on the evidence relating to how trees can capture air pollutants (with reference to riparian tree species where evidence is available) primarily in the urban environment. In the rural environment, agriculture ammonia and subsequent nitrogen deposition is more of a threat to semi-natural habitats such as river woodlands.

Beneficiaries

The beneficiaries from trees intercepting sources of pollution include Local Authorities, the National Health Service, the recreation, education and conservation sectors. The National Health Service will benefit from healthy respiratory and cardiovascular systems, and the educational sector in improvements in educational attainment and attendance of children which has been linked to air quality. Town planners in Local Authorities will be interested in tree mitigation measures as the National Planning Framework must have regard to Scottish Government's national strategy for improvement in air quality (Clean Air for Scotland 2). Woodlands along streams and rivers in towns will also benefit active travel and health. River woodlands will help separate pedestrians from traffic, creating safer walking routes, reduce the visual and noise effects of the traffic as well as allowing vehicle pollutants to disperse from the road therefore reducing their concentration in the atmosphere.

3.5.2 Capturing air pollutants

Functional processes

The biophysical processes involved in the ability of trees and woodlands to influence air quality are well known. Trees can act as biological air filters; their large leaf area relative to their ground footprint and the absorption properties of their surfaces enable them to remove certain airborne particles and improve the air quality of polluted environments through absorption and deposition (Beckett, Freer-Smith and Taylor, 1998, 2000) (in Binner *et al.*, 2017). Trees have the ability to capture air pollutants such as ultrafine particles (UFPs) associated with diesel vehicle exhausts (Wang *et al.,* 2019). Urban tree planting can reduce PM_{10} (particles smaller than 10 µm) concentrations (Fowler *et al.*, 2003; Bealey *et al.*, 2007). Figure 9 shows an example of urban river woodlands along the River Dee. Trees can also reduce the quantity of polycyclic aromatic hydrocarbons (PAHs) in the atmosphere by accumulating particles of less than 2.5 µm in diameter ($PM_{2.5}$) on the surface of leaves and bark (Jouraeva *et al.*, (2002). Also, greenhouse studies with intact soil cores have shown that the deposition of PAHs on soil beneath trees can lead to the degradation of particles by bacteria in the rhizosphere (Spriggs *et al.*, 2005). The rate of degradation or biotransformation of PAHs was greatest for soils with black willow (*Salix nigra* Marshall), followed by poplar, ash, and the unvegetated controls.

Apart from trees' ability to mitigate PM_{10}, trees can provide additional improvements in air quality, through the deposition and uptake of O_3, CO, SO_2 and NO_X. The proportion of gaseous pollutants absorbed depends on a number of factors; these include tree species, stomatal conductance, environmental conditions and pollutant concentration in the atmosphere (Broadmeadow & Freer-Smith, 1996).

Debate does remain however, regarding the efficacy of urban forests for improving air quality through pollutant deposition and absorption (in Binner *et al.*, 2017). Vos *et al.* (2013) note that urban trees can reduce wind flow, thereby preventing dilution and creating increased local pollutant concentrations. Other potential localised air quality problems associated with trees include the production of allergens such as tree pollen and the release of volatile organic compounds (VOC) that can combine with man-made oxides of nitrogen and contribute to the production of other pollutants. VOC emission is known to be dependent on different tree species, temperature and light (Fulton *et al.*, 1998).

Measured effect

Wang *et al*. (2019) found that silver birch (79% UFP removal), yew (71%), and elder (70.5%) have very high capabilities for capture of airborne UFPs. Metal concentrations and metal enrichment ratios in leaf leachates were also highest for the post exposure silver birch leaves; scanning electron microscopy showed that UFPs were concentrated along the hairs of these leaves.

The deposition of aerosols (PM_{10} in the form of ^{210}Pb) on woodland and grass was quantified at a range of locations throughout the West Midlands of England, ten km NE of Birmingham city centre (Fowler *et al*., 2003). The sites included mature deciduous woodland in Edgbaston, and Moseley, and mixed woodland at sites within Sutton Park. The soil inventories of ^{210}Pb under woodland exceeded those under grass, by between 22% and 60%, with dry deposition contributing 24% of the total input flux for grass and 47% for woodland. The aerosol dry deposition velocity to grassland averaged 3.3 mm s^{-1} and 9 mm s^{-1}) for woodland showing that the woodland collects the ambient aerosol or PM_{10} at approximately three times the rate of grassland. Furthermore, the large deposition rates of aerosols onto woodland relative to grass or other short vegetation (x 3), and accumulation of heavy metals within the surface horizons of organic soils, lead to high concentrations in soils of urban woodland.

The ecosystem services delivery of urban trees can be assessed using tools such as i-Tree Eco[24] which includes modelled quantified estimates for air pollution removal for 30 tree species including riparian woodland types (Hand & Doick, 2019; Hand *et al.*, 2019 a, b). i-Tree Eco utilises data collected in the field across the UK (including Edinburgh) to model each individual tree's leaf area, biomass, basal area, crown projection and general condition. Together with the in-built climate, air pollution and phenology data, the air pollution control provision by tree species is then modelled. Leaf area is calculated from species and crown parameters and assessed with existing relationships to estimate the interception of air pollutants. Air pollution removal is quantified for ozone, sulphur dioxide, and oxides of nitrogen and particulate matter which are less than 2.5 µm (PM2.5) and are reported both individually and as a total by i-Tree Eco to provide total pollution removal values. Results showed that larger stature tee species (such as Ash & Oak) ranked higher in their ability to remove air pollution than smaller stature trees but with some exceptions such as Scots pine (Hand & Doick, 2019). Air pollution removal for all stature trees (small, medium and large stature) was observed to increase with age peaking in either the over-mature or veteran age classification (Hand *et al*., 2019a, b). From the listing of species, many riparian tree species are of low to medium stature (see Hand & Doick, 2019). The best small stature species for air pollution removal were apple spp., goat willow and bird cherry, which were estimated to remove over 350 g of air pollutants per tree per year by the over-mature or veteran age classification. The highest rates of air pollution removal (>1000 g per tree per year) for medium stature trees were found in field maple, downy birch, Lawson's cypress and silver birch, based on both field-sampled and simulated data. In contrast, the other species removed just over half this quantity of air pollutants.

McDonald *et al.* (2007) predict from the application of an atmospheric transport model that increasing the total tree cover in the West Midlands from 3.7% to 16.5% could reduce PM_{10} concentrations in the West Midlands by 10%, removing 110 tonnes per year of primary PM_{10} from the atmosphere (in Binner *et al*., 2017). Tallis *et al.* (2011) provide evidence from the Urban Forest Effects Model[25] to support the hypothesis that targeted planting of broadleaved trees to expand the urban canopy of the Greater London Authority would provide a large benefit to future air quality through the removal of 1109–2379 tonnes of PM_{10} from the urban boundary layer. In particular, targeting of street tree

[24] More information available here: [i-Tree Eco | i-Tree (itreetools.org)]

[25] The Urban Forest Effects Model: This computer model for quantifying urban forest structure and functions calculates the structure, environmental effects and value of urban forests. The tool uses air dispersion and particulate interception models to predict the PM_{10} concentrations both before and after green space establishment

planting in the most polluted areas would have the greatest benefit to future air quality. The increased deposition would be greatest if a larger proportion of coniferous to broadleaved trees were used.

Factors influencing effectiveness

The potential air quality improvements provided by each tree depends on the species and maturity and stature of the tree (Freer-Smith *et al*; 2005; Hand *et al.*, 2019 a, b). The type of tree, whether it is a broadleaf, conifer, evergreen and/or deciduous, will affect its ability to intercept air-born pollutants. Conifer evergreen trees, for example, can take up pollutants all year round and throughout the night due to their open stomata, and they also have a higher leaf surface area (Broadmeadow and Freer-Smith, 1996). The concentrations of NOx and SO_2 are highest in winter and therefore evergreens have greatest influence on uptake of these pollutants. However, ozone is a significant problem in summer and so broadleaved trees are most effective at reducing levels of this pollutant (Broadmeadow and Freer-Smith, 1996). Donovan *et al.* (2005) quantified the species effect using a series of model scenarios to develop an urban tree air quality score; they considered 30 species and found that pine, larch and silver birch have the greatest potential to improve urban air quality, while oaks, willows and poplars can worsen downwind air quality if planted in very large numbers, which has been linked to their emission of biogenic volatile organic compounds. A mix of species is recommended.

Bark and leaf physiology are influencing factors as trees with rough or flaky bark or rough or hairy leaf surfaces trap and retain more air pollutants than tree species with smooth bark and leaves (in Hand *et al.*, 2019). Uptake of pollutants is lower during poor light and during drought, but the planting of suitable drought-tolerant species may maximise uptake during summer.

The design and siting of the woodlands can improve their effectiveness. Pollutant uptake has been found to be greatest at the canopy edge, as a result of reduced canopy resistance.

Urban river woodlands along River Dee in Aberdeen City have a role in buffering recreational spaces from ultra fine particulate pollutants from traffic (media.istockphoto.com)

UKCEH has developed guidance for the creation of new farm tree belts to capture ammonia downwind of agricultural practices [26], which includes a tool to calculate potential pollutant capture rates by the canopy. The rate of capture is dependent on the height and leafiness of the tree canopy and depth of the treebelt. The guidance recommends the woodland is within ten-20 metres of the source; with an open tree canopy to allow the plume of pollution to enter the woodland and a thick back-stop of trees or bushes to push the plume up into the upper canopy of leaves and prevent loss out the back of the treebelt. The tree canopy has an added benefit of

[26] CEH Farm Trees to Air Guidance Story Map Cascade

increasing dispersion of the plume, thereby lowering concentrations and deposition of harmful nitrogen pollutant to nearby protected nature sites.

Pollutant uptake is maximised where plants are exposed to high concentrations of the gases or particulates. Riparian tree corridors which are next to roads maybe the most efficient pollutant scavengers in a river woodland context. However, it is important to consider site-specific factors, such as soil quality and compaction, which may have an adverse effect on plant growth and so reduce the uptake of pollutants. Furthermore, if there is a build-up of any toxic substances from air pollution in the soils under the trees, the risk of leachate to near-by watercourses needs to be considered and in planning designs which can incorporate the right species choice and mitigation.

3.5.3 Evaluation of evidence

Strength of evidence (based on quality of studies)

Capturing air pollutants: The biophysical processes through which trees can capture pollutant particles are relatively well understood. There is **strong** empirical evidence from multiple lines of moderate evidence and process-based modelling that urban trees in the UK including riparian woodland types can capture air pollutants and reduce pollutant loads. Although there is quantified evidence from modelled data that urban woodland can reduce PM_{10} levels at larger spatial scales, there is limited evidence for urban riparian woodland networks.

Limitations and gaps in research

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. As targeting pollution hotspots is important, the location of trees next to streams and river courses in potentially restricted spaces is a limitation. However, roads often follow river courses and people are attracted to them for health and active travel and so this can be seen as active targeting for multiple benefits.

Research is needed to transfer design understanding from farm woodlands and urban woodlands more generally to design of urban riparian woodlands. In particular, there is a need to understand the risks associated with pollution swapping from air to soils to water and how these risks can be mitigated against. Further understanding of how 3D concepts for rural diffuse pollution mitigation (see section 3.1.2) can be transferred will be beneficial especially where above and below ground space is restricted by development and drains.

Most empirical evidence from field studies focuses on highly localised benefits from tree induced air quality improvements for urban trees in general. Further study is needed to determine impacts from riparian tree species in a riparian woodland context and for modelling to integrate riparian woodland networks on a larger spatial scale.

For trees/woodlands in the rural landscape, agricultural ammonia and subsequent nitrogen deposition is the main air pollutant threat to semi-natural habitats including river woodlands. Research has focused on ancient woodlands and effects on lichens and bryophytes from Nitrogen pollution, but not on river woodlands per se. At the same time, trees act as good scavengers of N pollutants (Bealey *et al.,* 2016; Theobald *et al.*, 2001), hence more research is required on the N balance and potential leaching after canopy capture.

3.6 Sustaining soils

3.6.1 Overview of benefit

River woodlands can help improve and sustain soil health and contribute to safeguarding this important natural resource by reducing soil loss via erosion. Healthy soils are more resilient to degradation, and thus protect the wider environment and society from the impacts of pressures including climate change. Future climate projections provide strong evidence that climate risk to soils will increase in Scotland. Heavier rainfall events could result in erosion, compaction, and pollution. Increases in soil moisture deficits in summer could lead to loss of soil biodiversity and poor soil health. (Climate Change Risk Assessment 3).

This section focuses on how planting river woodland trees can help sustain soils by two main functions of improving soil health and reducing soil loss. Links to the wider environmental benefits provided by healthy soils for environmental resilience will be highlighted under that function.

Beneficiaries

Arable and livestock farmers will benefit from trees stabilising soil on the bank and within the riparian zone, which reduces the risk of soils being washed away downstream. Riparian landowners and tenants will benefit from not having to dredge the soil out of rivers as it has been stabilised on the land by tree roots. Native woodland owners and foresters will benefit from healthy forest soils ensuring good tree growth and carbon storage. Fishery managers, conservationists and all water users will benefit from healthy riparian woodland soils due to their contribution to nutrient cycling on land, but also in the water, supporting cycles of life and clean water, encouraging improved aquatic biodiversity and reducing water treatment costs.

3.6.2 Improving soil health

Functional processes

Planting riparian woodland can help improve soil health by improving soil structure, adding organic matter and providing a home for plants, animals and micro-organisms. The main reason for these improvements is the substantial reduction in soil disturbance under trees compared with bare soil.

Planting trees can benefit soil structure which is the arrangement of solids and pore spaces (gaps) within soils which influence soil water and air movement. The pore spaces facilitate the infiltration, movement, and storage of water in the soil, as well as gas exchange. Given that most soil organisms, including the tree roots, require oxygen but produce carbon dioxide this gas exchange is essential. Regular soil disturbance not only destroys the physical structure but also the root and fungal systems that help to create soil aggregates. Soil disturbance may also kill pore-creating soil animals, such as earthworms.

Mycorrhizal fungi have a role in enhancing aggregation and binding soil particles; their mycorrhizal mycelium is a sticky living seam that can hold soil together, so removing the fungi can lead to the ground washing away (Sheldrake, 2020). The hyphae of endomycorrhizae secrete glomalin that aggregates soil particles, increasing water-stable aggregates and improving soil structure (Kennedy & Luna 2005). The soil binding process can lead to a reduction in soil nutrient losses (Asghari & Cavagnoro, 2012; Qiu *et al.*, 2022). Asghari and Cavagnaro (2012) highlight the need to maintain and enhance mycorrhizas in vegetated buffer strips between potential sources of nitrogen pollution, such as farms and urban areas, and potential sinks for nitrogen, such as natural lands and water bodies.

Temperate woodland soils (litter layer, topsoil and subsoil) including native riparian woodland and floodplain woodland soils are known to store large quantities of organic carbon (Sutkin *et al.*, 2016).

The floodplain surface and shallow subsurface can host a large reservoir for organic carbon including surface organic layers and soil organic carbon (SOC). Surface organic carbon input derives from plant litter in various stages of decay and includes leaves, small branches, twigs, recently died understorey riparian plant material as well as from root litter (dead roots, fine roots can get replaced daily) and rhizodeposits (exudates coming from the roots).

Mycorrhizal fungi attached to roots and in the soil also stores carbon. Mycorrhiza fungi receive organic molecules directly from trees in exchange for nutrient and water provision, which they use to build their extended mycelium and therewith distribute the carbon throughout the soil. The carbon of fungi hyphae is more stable than root exudates due to their chemical structure, therefore fungi are likely to play an important role in carbon sequestration. Although most carbon will be placed on or close to the soil surface, some will be locked in deeper parts due to tree roots transporting carbon into deeper layers. Organic matter located within aggregates or in greater soil depth is less available to microbial attack and therefore less prone to decomposition. Soil disturbance can bring deeper soil to the surface and destroy aggregates and thereby cause release of stored organic carbon (Mayer *et al.* 2020).

Soil biodiversity underpins most soil functions, such as decomposition, nutrient cycling, breakdown of pollutants, as well as pest control and supporting above-ground biodiversity, thereby underpinning the ecosystem (section 3.7). It is the high heterogeneity of soils, underpinned by good soil structure, with various gradients in moisture, carbon (food), nutrients and oxygen, that provides nearly infinite microhabitats. Each microhabitat maintains local diversity in a soil microbial community (Wang *et al.* 2021).

It has been shown that soil heterogeneity is higher in native woody habitats compared to grassland (Curd *et al.* 2018 and literature cited therein) and that land use intensification reduces the complexity in the soil food webs (Tsiafouli *et al.* 2015), indicating that woodland soils contain a higher soil biodiversity and more complex food webs than other land uses, making them more resilient. Woodland soils show higher abundance and species diversity of fungi and archaea compared to grassland soils, whereas these are larger for bacteria in grassland soils (Banerjee *et al.* 2018). There is some evidence that mycorrhizal fungi associated with riparian woodlands may be different from other temperate woodland soils due to the influence of flooding (see factors influencing effectiveness below).

Riparian and floodplain woodlands promote sediment deposition and retention of the organic material which comes with it, which carries nutrients that can fertilise alluvial floodplain soils (Hughes, 2003). In the UK, there is evidence that, during flood events, the amount and pattern of sediment deposition is greater and more variable on areas of forested floodplain in the New Forest in southern England than on the non-forested floodplain (Jeffries & Sear, 2003) (see section 3.3.3). Soil formation and the build-up of soil organic carbon varies according to the distance from the river and the type of riparian woodland community. For example, a study on the Danube in Austria of different riparian woodland types found hydro-ecomorphological conditions in the riparian zone drive soil formation. For example, riparian forest close to the river had alternate phases of sedimentation and soil formation, linked to coarse sediment deposition during large flood events and more stable soil building periods between these events. Whereas riparian forest distant to the river, had slower flowing water during flood events with higher clay fractions in the sediment. This enables sedimentation and soil formation to occur simultaneously. The burial of organic matter in the active floodplain close to the river enables conservation of carbon in the buried layers (Graf-Rosenfellner *et al.*, 2016).

Healthy soils under river woodlands will be more resilient to pressures including climate change impacts and will provide a range of multiple benefits. This includes benefits detailed in other sections of this report:

- Protecting water quality (section 3.1):
    - Improving chemical, physical and microbial processing via retention onto soil particle surfaces and microbial uptake will help to reduce pesticide concentration in runoff flowing through man-made riparian buffers (section 3.1.5).
    - Underpinning the function of man-made riparian woodland buffers in capturing pathogens (section 3.1.6).
- Providing resilience to drought (section 3.2):
    - Intact soil structures are more likely to aid the retention of soil moisture and hydraulic lifting during dry conditions (section 3.2.2)
- Reducing flood risk (Section 3.3):
    - Improved water infiltration and increased water holding capacity will result in less run-off and erosion reducing the risk of flooding (section 3.3.3) and water pollution.
- Improving carbon storage (Section 3.4);
- Conserving biodiversity (section 3.7):
    - by supporting healthy habitats above and below ground (section 3.7).
    - nutrient status of riparian woodland trees and their soils influencing in-stream nutrient cycling and the fertility of alluvial sediment deposits on floodplains downstream aided by floodplain woodland (section 3.7.3).
- Enabling good health by assisting in heat wave management in greenspaces to cool our towns and cities (section 3.8.3).

Measured effect

Quantitative data on the benefits of river woodlands or even woodland in general for soil health is very limited; in particular, data on benefits for soil physical properties and biological properties and biodiversity are usually severely lacking. There are some woodland studies which have quantified the effect of trees on soil biodiversity and the development of essential mycorrhizal associations for nutrient recycling and carbon storage but these are restricted to woodlands in general and not directly focused on different types of river woodlands (see section 3.7.4).

The monitoring of soil conditions under fenced riparian woodland buffer strips in the Tarland Catchment of the River Dee in Aberdeenshire found the soils to be more nutrient-rich than unbuffered strips; a likely consequence of decomposing plant litter which has been able to accumulate without disturbance (Stockan *et al.*, 2012). These characteristics were more pronounced where there was a greater percentage of native tree species.

Scientific understanding of the functional role of mycorrhizal fungi in enhancing aggregation and binding of soil particles is improving. However, the focus is on laboratory studies, and processes in woodland soils and riparian woodland have not been studied. Laboratory studies are starting to quantify the nutrient retention and cycling role of fungi. A meta-analysis of 36 laboratory studies of using mycorrhizal inoculum found the presence of arbuscular mycorrhizal fungi significantly reduced soil nitrogen and phosphorus losses, with the most pronounced reduction occurring in soil nitrate nitrogen (−32%), followed by total phosphorus (−21%), available phosphorus (−16%) and nitrous oxide (−10%) compared with controls (Qiu *et al.*, 2022). Other laboratory experiments found that mycorrhizal root systems dramatically reduced nitrate loss (almost 40 times less) via leaching, compared to their nonmycorrhizal counterparts, following a pulse application of ammonium nitrate to experimental microcosms. The difference was only partly explained by improved nutrient uptake by the plants (Asghari & Cavagnaro, 2012). It is not clear if mycorrhizal fungi contribute to the more nutrient rich soils found in woodland buffer strips research.

A single study from the USA has attempted to quantify the carbon sequestration from mycorrhizal fungi. Ouimette (2020) measured the contribution of mycorrhizae fungi to carbon storage in woodlands. They measured annual production of plant components (foliage, wood, fine roots) and mycorrhizal fungi across temperate forest stands varying in species composition, in an established forest in New England, USA. Production of mycorrhizal fungi was estimated using both mass balance and isotopic techniques. Total plant production varied from about 600 g C m^{-2} y^{-1} in nearly pure deciduous broadleaf stands down to about 300 g C m^{-2} y^{-1} in conifer-dominated stands. In contrast, the production of mycorrhizal fungi was highest in conifer-dominated stands, varying from less than 25 g C m^{-2} y^{-1} in deciduous broadleaf stands to more than 175 g C m^{-2} y^{-1} in nearly pure conifer stands.

Soil organic carbon (SOC) associated with floodplain forests has been measured in a single study of hard wood floodplain forest and grassland sites on the Elbe. This study found that forest SOC stocks ranged between 99 and 149 t ha^{-1}. SOC stocks decreased with depth throughout all categories and were unaffected by vegetation type within the same hydrologic situation. Vegetation parameters such as age, basal area, or leaf litter carbon stock had no direct effect on SOC stocks. An active connection to the river had the strongest effect on SOC stocks, with former floodplain sites storing 33% less SOC than the active sites. Within the active floodplains, low sites stored 50% more SOC than high sites. This effect was mainly controlled by relief-affected features such as flooding duration and fine texture, which also were the strongest univariate predictors for SOC stocks ($R^2 = 0.39$ and 0.63) (Heger *et al*. 2021)

Factors influencing effectiveness

It is important that the right tree is planted in the right place so that the net carbon balance is positive rather than negative, soil structure is improved, and stabilised, and suitable habitats are created to improve soil biodiversity (which may, in turn, also benefit above ground biodiversity). Selecting the right mixture of tree species to plant depends on a wide range of factors, including soil type/depth, local climate and topography, river morphology and surrounding land use.

Soil moisture regime and flooding frequency is likely to influence the ability of river woodland soils to store carbon. Sutkin *et al*., (2016) describes how the moist conditions of riparian soils facilitate increased metabolism of soil organic carbon (SOC) by microbes, whereas saturated conditions associated with shallow water tables decrease metabolism and increase potential long-term storage. The review suggests that continued aggregation and burial of floodplain soils may contribute to high rates of carbon sequestration.

The frequency and magnitude of flooding has been found to affect the type and amount of mycorrhizae fungi in river woodland soils. For example, a study of mycorrhizal fungi associated with different ages (10,20 and 60 years old) of willow- dominated riparian forest in the Netherlands found that only a limited number of mycorrhizal fungi species can resist the effect of flooding with the frequency of it occurring on less than 9% on root tips at all sites. (Paradi & Barr 2006). In a field study that measured the mycorrhizal fungi in an established willow short rotation coppice plantation (14 years old) in England, extreme flooding was also associated with a crash in the richness and relative abundance of ectomycorrhizal fungi with each declining by over 50% compared to stable conditions prior to flooding and relative abundance declined by two thirds, whilst richness and relative abundance of saprophytes and pathogens increased during the same time period. (Barnes *et al*., 2018). These studies indicate that findings for woodland soils in general cannot be applied wholescale to riparian woodlands dominated by willow.

Other studies of riparian cotton woods in the USA found that flooding was a key element to influencing the type of mycorrhizal fungi and its effectiveness in soil aggregation. They found that the formation of water stable aggregates increased rapidly during the first third of the chronosequence, which was the period of greatest arbuscular mycorrhizal fungi (AMF) abundance in the soil. The peak in AMF infectivity and hyphal length during early succession (first 13 years) suggests that regular flooding and establishment of new sites promotes AMF abundance in this ecosystem (Piotrowski *et al.*, 2008)

3.6.3 Reducing soil loss

Functional processes

River woodlands can reduce soil loss and soil erosion from riverbanks and hillsides, safeguarding soils as an important natural resource and reducing the risk of the soils being washed away. The tree roots stabilise the soils and the canopy reduces the physical impact of raindrops, leading to fewer particles being detached from the soil surface and therefore lost to river water through runoff. Riparian woodland buffers and large woody material can trap sediment, reducing diffuse pollution (section 3.1.4) and flood risk (section 3.3.3).

Measured effect

There is very strong empirical evidence from the international literature that tree roots stabilise riverbank soils (section 3.1.4). In the UK, measurements generally show consistently lower soil losses from the bank and greater bank stability for watercourses lined by riparian woodland, compared to other land uses (section 3.1.4). Using satellite imagery and a model of river channel migration, Horton *et al.*, (2018) found that the cumulative economic losses from agricultural land (and soil) loss from bank erosion are higher in the absence of a forest buffer than when a buffer is left intact.

There are many studies which measure positive effects of retaining sediment pollution by active tree planting management in riparian buffer zones (section 3.1.4). Modelling with root cohesion parameters has also shown that when trees are strategically placed in the catchment along soil erosion source-flow pathways, they can reduce the course sediment loads entering rivers significantly (Lane *et al.*, 2008) (section 3.3.3).

Factors influencing effect

It is important that the right tree is planted in the right place so that benefits of reducing soil erosion on riverbanks are maximised. For more detail see factors influencing effect from the linked sections highlighted above.

3.6.4 Evaluation of evidence

Strength of evidence (based on quality of studies)

Improving soil health: there is a **strong** understanding of the biophysical processes which underpin the ability of trees and woodlands to improve soil health. Empirical evidence for measured positive effects on soil structure, soil organic carbon, biodiversity and soil fertility remains **weak** for native floodplain and riparian woodlands.

Reducing soil loss: Overall the evidence that trees reduce soil loss is **strong** from an analysis of all relevant functions relating to soils in other sections. There is very strong empirical evidence from the international literature that tree roots stabilise riverbank soils. There is strong empirical evidence from site-based experiments that riparian woodland can reduce suspended solids compared to controls at the field scale. There is evidence from the SEDMAP model that strategic planting in an upland catchment in Northern England reduces coarse sediment loading at the catchment scale significantly.

Limitations & Gaps in Research

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.

Further studies are required to measure the effect for river woodland types that takes account of their location in relation to the river and flooding regime.

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.

Further field data is required to understand differences in carbon storage in different types of river woodlands and river systems in Scotland (section 3.4.3). The Scottish Forest Alliance project will contribute to understanding the changes in carbon stocks in vegetation and soils over time on sites which include new riparian and floodplain woodlands. The mycorrhizae element of carbon storage is not normally included in native woodland estimates for carbon and requires further consideration.

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).

3.7 Conserve biodiversity and ecosystems

3.7.1 Overview of benefit

River woodlands have a critical role in supporting biodiversity as the trees provide a range of functions that support other species across the ecosystem. There are complex, interlinked relationships between the trees and associated large woody material, water, sediment and other living organisms.

River woodlands play crucial roles in key aquatic and hydromorphological processes which promote aquatic and terrestrial biodiversity. They provide a habitat for a range of species including threatened and rare species of paramount conservation concern protected by European and UK conservation legislation. Floodplain and riparian woodland corridors provide opportunities for gene flow between populations of tree species, seed dispersal and allows for the migration of plants and animal species.

Habitat loss and habitat fragmentation from land cover change (e.g. deforestation for agriculture) is a main driver for the loss of biodiversity worldwide and in Scotland (Hassan *et al.*, 2005). Natural river floodplains are among the most biodiverse and productive ecosystems in the world (Tockner *et al.*, 2000) (in Keruzoré *et al.*, 2012). Nevertheless, floodplains have been heavily reduced by human activities. At present in Europe at least 90% of the area of floodplains has disappeared through channel straightening and embankment (Tockner and Stanford, 2002). The main drivers for such reductions are flood control, navigation, hydropower and agricultural expansion. No such figures exist for the UK, but it is widely acknowledged that floodplains have been modified very extensively for agriculture (Bailey *et al.*, 1998) (in Keruzoré *et al.*, 2012). River flow regulation and reduction dictate that channel and flow dynamics are increasingly disconnected from floodplain ecosystems. Thus, near-natural examples of large, ecologically intact rivers have become very rare (in Keruzoré *et al.*, 2012). Based on SEPA's 2015/2016 surveys of riparian bank vegetation, and remotely sensed data use in the Morphological Impact Assessment System (MImAS) for Scotland's River baseline network, 56% of the banks were in poor quality with a lack of riparian woodland habitat (see section 1.2) with no diverse vegetation structure or composition.

Climate change is having a dramatic impact on our natural environment and is also a direct driver of biodiversity loss. Restoring riparian woodland has the potential to enhance woodland habitat network connectivity and biodiversity and thus resilience to climate change at the landscape scale. Scotland's Biodiversity Strategy aspires to have a national ecological network[27], and restoring a riparian network through Riverwoods could make a major contribution to the establishment of this network, to enable greater resilience for Scotland's biodiversity to climate change.

This section seeks to highlight the evidence for how river woodlands support aquatic processes (shading and nutrient cycling) and hydromorphological processes which, in turn, support biodiversity, rather than identify all the biodiversity that they support. The evidence is presented under the main functions of providing a variety of light conditions, supporting nutrient cycling and food webs, supporting other species via habitat provision, providing habitat connectivity, supporting genetic diversity, and supporting river hydromorphological processes and diversity. As it is difficult to collate quantified measured effects such as population level changes with remnant river woodland status in Scotland, evidence on measured effect has not been separated out so much in this section, apart for the function relating to hydromorphology.

Beneficiaries

The beneficiaries of biodiversity and ecosystem conservation span all businesses, organisations and institutions in Scotland as this benefit provides natural resources and resilience against climate change, which is a major threat to humanity. Biodiversity is core to the ecological condition and quality of ecosystems that support the services provided to people. It directly benefits people through species existence, through nature-based solutions and by enriching other benefits (like nature-based recreation). It also underpins the resilience of ecosystems to shocks and can provide insurance value[28]. There is, therefore, an overlap with other benefits identified in section 3 of this report. River woodlands provide direct and indirect cultural benefits to people not covered elsewhere in this report; for example, wildlife watching experiences that enrich the experience of visitors and tourists in Scotland, helping to support wildlife watching businesses, and tourism businesses that provide accommodation. Estates, nature conservation organisations and other riparian landowners create walks and tracks through river woodlands as part of their visitor attractions. Biodiversity is intrinsic to that experience.

3.7.2 Providing a variety of light conditions

Overall, biodiversity in the river benefits from a range of different light conditions through direct and indirect effects; riparian woodlands have a role in providing this diversity of light conditions. For example, there are complex relationships between riparian trees and algae. It has been found that attached microalgae and diatoms are more significant in providing protein and other essential nutrients to grazers than terrestrial sources of nutrients from leaves from riparian trees. These algae are found on all surfaces within the river. Increases in sediment due to loss of riparian woodland can impact attached microalgae, favouring filamentous and stalked algae and motile diatoms and cyanobacteria which have lower nutritional value (Vadeboncoeur & Power, 2017). However, riparian trees also shade the watercourse, influencing the communities of algae that provide a key source of food and habitat in the ecosystem (see section 3.1.7).

In terms of the risk of climate change to insects with riverine life stages, such as mayflies, stoneflies and caddisflies, a recent study (Macadam *et al.,* 2022) identified 16 species of river flies in the UK which are vulnerable to climate-mediated temperature increases in rivers (with examples from both

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[27] More details about the national ecological network are in priority action 10 Scotland's biodiversity: a route map to 2020 - gov.scot (www.gov.scot)

[28] Enabling a Natural Capital Approach guidance - GOV.UK (www.gov.uk)

lowland and upland rivers). Increasing the amount of shading for river through riparian tree planting is the primary measure they propose to address this (along with other catchment-scale changes). The empirical evidence that demonstrates the link between shade provided by river woodlands to help regulate water temperatures in summer, is presented in section 3.9.

3.7.3 Supporting nutrient cycling and food webs

Importance of deciduous trees

Autumn leaf-fall from deciduous trees provides an important food source to freshwater macroinvertebrates (MacKenzie, 1996). The nutrient status of the bankside trees and the soils influences the nutrient content of the leaves which fall in the water and eaten by the invertebrates. There is evidence that nitrogen is of critical nutritional importance to these stream detritivores, with the nitrogen content of leaves of broadleaves, particularly Alder, being higher than conifers (MacKenzie, 1996). There is evidence that a mixed broadleaf woodland canopy of native species is most effective to ensure a range of leaf litter quality with different broadleaf species having different decomposition rates from quick (Alder) to slow (Oak) (Chauvet *et al.*, 2016).

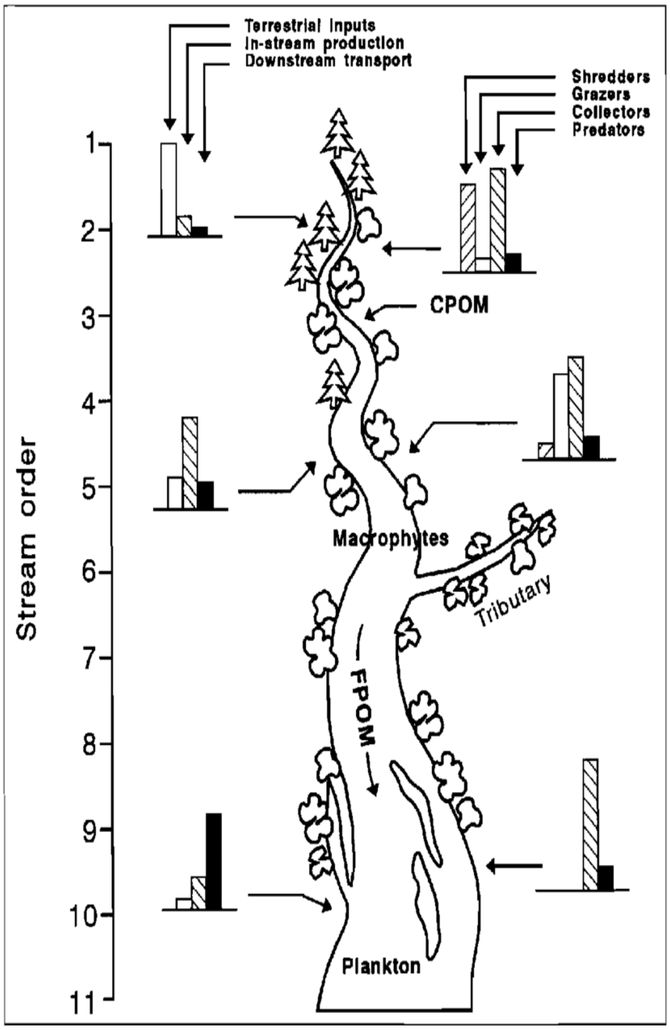


Figure 8: River Continuum Concept from Mackenzie, 1996

According to Mackenzie's review, the quantity and diversity of leaf litter in streams has a direct bearing on the biomass of invertebrate consumers and, ultimately, on the numbers of both predatory invertebrates and fish within the stream ecosystem. Many studies provide evidence to show the influence of the riparian vegetation on the aquatic invertebrate assemblage structure, function and productivity. In woodland streams, shredders play an important role in the conversion of leaf litter from Coarse Particulate Organic Matter (CPOM) into finer particles (FPOM) (Webster & Benfield, 1986; Cuffney *et al.*, 1990; Thompson & Parkinson, 2011) and biomass which, in turn, provides food for collectors which are unable to process the coarser fractions. Thomas *et al.*, (2016) found, in Wales, that streams draining deciduous woodland differed clearly from others in having substantially enhanced standing stocks of CPOM, as well as a greater density and biomass of macroinvertebrates, particularly shredders. Stream-scale investigations showed that macroinvertebrate biomass in deciduous woodland streams was around twice that in moorland streams, and lowest of all in streams draining non-native conifers (Thomas *et al.*, 2016). The algae and invertebrates support and provide food for fish. This is covered in more detail in section 3.9.

Food for aerial animals
Invertebrates provide food for aerial birds and bats. For example, wooded riparian habitats and the adjacent freshwater provide excellent foraging habitat for bats. A study on the Rivers Lee and River Colne catchment in England, found that a degradation in the quality of riparian woodland habitat reduced foraging and activity in pipistrelle bats (Scott *et al.*, 2010). Increases in foraging and activity was thought to be linked to higher invertebrate abundance or greater safety from predators. A study in North Wales by Todd & Williamson (2019) found that three species, Daubenton's bat (*Myotis daubentonii*), common pipistrelle, (*Pipistrellus pipistrellus*), and soprano pipistrelle (*Pipistrellus pygmaeus*), preferred river sections with smooth water and trees on either one or both banks. Daubenton’s bats, also known as water bats, have a preference to roost close to riparian woodland edges to minimise energy expenditure in flying to feeding sites across the water where they trawl for aquatic insects such as Diptera which form a main part of their diet.

Longitudinal transfer of nutrients
The River Continuum Concept illustrates and highlights that native riparian woodland in the headwater catchments are important for the ecological functioning of the whole river network (McKenzie, 1996) (Figure 8). The main energy base starts with the forested headwater streams upon which much of the downstream productivity depends. The energy sources are based on terrestrial leaf litter and large woody material from the bankside trees, terrestrial invertebrates and dissolved organic matter derived from soils. The main invertebrate groups which feed on this material are shredders and collectors. As the streams become larger, the influence of the riparian woodland is reduced and so is the leaf litter input. In middle sized rivers, where there is more light, more primary production occurs where energy is captured from the sun by plants. The main invertebrate groups are grazers and collectors. In large rivers, primary production is reduced due to turbidity and the main energy source becomes the particulate organic matter transported from upstream and inputs from the floodplain. The main invertebrate functional groups are now the collectors. (Mackenzie 1996)

Lateral transfer of nutrients
Nutrients are also transferred laterally to land as well as downstream. For example, nutrients are captured and locked up in freshwater insect larvae that later emerge as flying adults which, when they die, represent an aquatic nutrient subsidy to land. Riparian trees also provide shelter for aquatic insects which they use after emerging from the river as adults. For example, the March brown (*Rhithrogena germanica*) emerges from the water in March/April and flies into the trees where they will rest before their moult to the final adult stage (Lubini & Sartori, 1994). The larvae of some species of dragonflies and stoneflies climb up riparian trees to emerge as an adult.

River woodlands are used by adult stages of aquatic insects for breeding (Scottish Wildlife Trust)

Flowing water, especially flood water, transports both organic and inorganic matter which is deposited on the floodplain. This matter, especially the inorganic fractions such as silts and clays, carry nutrients that fertilise floodplains (Hughes, 2003). In reaches with high flow velocities, floods can scour floodplains and remove the organic matter, including vegetation, wood and leaf litter, organisms and upper soil layers. In slower flowing sections, floods may deposit much of the transported organic matter. The floods thus redistribute organic matter within and between floodplains and during this redistribution, the organic matter is processed by bacteria, fungi and invertebrates in the river and on the floodplain (Hughes, 2003) In flooding events, the presence of floodplain woodland will act to slow the flow and encourage out-of-bank flows, promoting sediment deposition and retention (section 3.3.3) and the organic material that comes with it.

Nutrients move downstream but also upstream from sea. There is research work which has explored the crucial role of migratory fish returning from marine ecosystems in providing nutrient input to upland river systems, with both riparian woodland and salmon carcasses providing sources of nutrients (e.g. Lyle & Elliott, 1998; McLennan *et al.*, 2019). McLennan *et al.*, 2019 found that deforestation in the uplands has resulted in loss of nutrients to rivers in the Conon catchment. The research found that the nutrient release from parental carcasses increase the growth, biomass and genetic diversity of juvenile Atlantic salmon. Lyle & Elliot (1998) provide estimates of fluxes (mean annual values) between freshwater and marine environments of organic carbon (C), nitrogen (N) and phosphorus (P) transported by migrating Atlantic salmon and sea trout in a group of seven rivers in NE England between 1989-1995). The net marine import of each element represented approximately 75% of the gross adult fish import. Migratory fish provide the one direct source of such materials to the upper reaches of rivers.

Temporal influence

There is a seasonal influence for the annual life cycle of some groups of animals. For example, in temperate deciduous forests in Japan it was found aquatic prey was found only in riparian forests and the biomass peaked in early spring, while terrestrial prey was equally distributed between habitats and increased in biomass in late spring. Bird density was higher in riparian than in upland forests before bud break, when the biomass of aquatic insects peaked, but was similar in both forests during the rest of the seasons. These results suggest that aquatic prey subsidies are used not only by birds inhabiting riparian forests, but also by birds associated with upland forests. Aquatic prey subsidies may be particularly important in the spring as a critical food resource for survival and the breeding activities of birds, thereby, influencing the population dynamics of bird communities. (Uesugi & Murakami, 2007). A similar temporal influence was found for fish (see section 3.9.3).

3.7.4 Supporting other species

Beavers

River woodlands support species which in turn affect the structure of the woodlands and the range of biodiversity they support. For example, European beavers (*Castor fiber*) are semi-aquatic mammals, closely associated with freshwater and riparian woodlands. They are described as ecosystem engineers because they physically alter their habitat by cutting down trees, building dams, digging canals and building lodges (Gaywood *et al.*, 2015; Brazier *et al.*, 2021). After a Scottish reintroduction, beavers' modifications increased the volume of standing dead wood and wood material and created a graded edge between the terrestrial and aquatic habitats that is rich in structural complexity. In doing so, and with beavers being selective foragers, they fundamentally increased habitat heterogeneity and, more widely in Scotland are expected to affect woodland tree species composition, age structure and ecological functioning (Gaywood *et al.*, 2015). Beavers have also been found to have had an overall positive impact on biodiversity (Stringer & Gaywood, 2016) including macrophyte species richness. There is evidence that beavers play a key role in restoring rivers to healthy resilient ecosystems and provide environmental benefits such as reducing flood risk, increasing water storage and improving water quality (Puttock *et al.*, 2017, Geris *et al.*, 2022).

Dams created by beavers in the headwaters of the River Tamar catchment significantly increased water storage within the landscape. During storm events, beaver activity had an attenuating impact upon high flow; leading to an increase in peak rainfall to peak discharge lag time, lower peak discharge and lower total event discharge (Puttock *et al.*, 2017). Event monitoring of water entering and leaving the site showed lower concentrations of nitrogen, phosphate and suspended sediment leaving the site which resulted in lower diffuse pollutant loads and improved downstream water quality.

In some situations, beavers can have a negative impact on other local interests such as farms, gardens and other land. NatureScot have produced a Scottish Beaver Management Framework to help ensure potential benefits are realised whilst minimising the detrimental impact on other interests. The CREW report provides an in-depth systematic review and analysis of the strength of evidence in relation to beavers in a Scottish context detailing benefits, disbenefits and research gaps (see Geris *et al.*, 2021).

Species of conservation concern

The conditions provided by riparian woodland support species of conservation concern and protected species under European and UK conservation legislation. For example, riparian woodland provides good instream habitat for the freshwater pearl mussel (*Margaritifera margaritifera*) where Scotland contains many of the world's most important populations of this critically endangered mollusc. The distribution of mussels was highly significantly associated with the presence of riparian broadleaf/mixed woodland in the River Spey, north-east Scotland (Hastie *et al.*, 2003). The mussel beds are often found in association with bankside trees where they benefit from the clear water (the tree roots stabilise the riverbanks) and shade which can reduce fluctuations in water temperature and prevent excessive algal growth on the river bed (Baer, 1981; Lucey, 1993). The life cycle of the freshwater pearl mussel includes a short (five-ten month) parasitic larval phase on the gills of juvenile salmon. The distribution of mussels may be influenced by the physical habitat preferences of host fish which are also attracted to the trees.

Riparian woodland is the natural habitat for the otter and water vole, which are two important and threatened mammal species. Otters create their holts within the expose roots of mature riparian trees (but also use rock fall in Scotland) and water voles prefer well-vegetated stream banks with suitable burrow sites safe above winter flood levels and open areas of tall tussocky herbaceous vegetation (in Broadmeadow & Nisbet., 2004).

Terrestrial plants, animals and insects

Man-made woody riparian buffers, whilst less biologically diverse than natural forest have been found to provide benefits to biodiversity. Field studies in Northeast Scotland have investigated and quantified vegetation patterns and plant environmental relationships (Stockan *et al.*, 2012) and ground beetle assemblages (Stockan *et al.*, 2014) within three categories of riparian margins in the Ugie catchment and Tarland Burn catchment. The margins were categorised as unbuffered (sites with no permanent fencing), buffered (sites with fencing with varying age from one to ten years and reference (target sites characterized by mature, woody riparian vegetation where agricultural activity had not taken place in the recent past).

Results showed that buffering had no effect on plant species richness within the Ugie after ten years but did have a significant effect on plant species richness within the Tarland catchment because plant species richness declined with the age of the buffer strip (Stockan *et al.*, 2012). This could be related to an increase in the abundance of bryophytes, whose abundance increased significantly between unbuffered, buffered and reference sites. It is known that bryophytes are able to outcompete vascular plants in more stable less disturbed areas with suitable moisture conditions. The finding of declining species richness is also in agreement with general ecological theories that there is a fall-off in species richness as biomass increases or as disturbance declines and it cannot be assumed that protecting more pristine systems will be positively correlated with protecting higher levels of plant biodiversity.

The abundance of other specialist riparian plant species (apart from bryophytes) was found to be higher at unbuffered sites compared with buffered and reference sites (Stockan *et al.*, 2012). Tree species were recorded across all sites and tree number and tree species richness were significantly higher at reference sites. The presence of a tree canopy appeared to be the key instigator of change in soil conditions and corresponding plant species assemblages. Results also showed marked geographic variation between the two catchments with a strong influence of nitrogen and phosphate reflected in the vascular plant assemblages.

Catchment and treatment effects were detected on ground beetle (*Coleoptera, Carabidae*) activity density and species diversity (Stockan *et al.*, 2014). Although the Tarland catchment was more species rich than the Ugie catchment (a more intensively managed agricultural landscape), unbuffered sites were higher in species richness than both vegetated buffered and wooded sites. The Tarland catchment is the smaller of the catchments but still had significantly higher values for species richness and diversity. A possible explanation is that greater habitat diversity within the Tarland catchment has the potential to increase the species pool. Buffered strips within the Tarland catchment showed greater environmental variability particularly with regard age, length and soil phosphorus. These features could create a diversity of niches and habitats, further increasing the potential species genetic pool.

Forested riparian buffers are initially relatively uniform and become more structurally complex as they grow providing micro habitats. (http://my.ilstu.edu/)

Research has found that over time, as trees establish and grow within buffer strips, the strips become more structurally complex (e.g. leaf litter, dead wood, woodland canopy) which has the potential to provide a greater variety of microhabitats for different types of species.

The abundance of small mammals and amphibians and reptiles increased with complexity of vegetation structure in a field study in Southern Quebec (Maisonneuve & Rioux, 2001). Small mammal diversity was higher in herbaceous and wooded riparian strips, whereas the amphibian and reptile community were more diverse in shrubby strips. Proportion and abundance of pest species diminished with complexity of vegetation structure, whereas insectivores increased in abundance. Maisonneuve & Rioux (2001) conclude that maintaining woody vegetation in riparian strips should increase abundance and diversity of wildlife within agricultural landscapes.

Soil biodiversity

A study on the Isle of Rum showed that in areas of woodland re-established on moorland, earthworm communities were significantly increased in number (up to 170 m^{-2} with a mass of 25 g m^{-2}) and diversity compared with open moorland (Butt & Lowe, 2004). It is suggested that some of the earthworm species have a role in assisting soil development and woodland establishment. Other research has found significant increases in total fungivore and predatory nematode abundance in birch and pine root presence treatments with total and fungivore abundances positively related to root biomass (Keith *et al.*, 2009). This is evidence to suggest that below ground tree inputs have a strong impact on soil food web structure and complexity.

3.7.5 Providing habitat connectivity and supporting genetic diversity

Restoring connectivity between remnant patches of riparian woodland and floodplain woodland is important for biodiversity. It has been found that non-coniferus riparian woody vegetation can increase landscape connectivity for adult Ephemeroptera, Plecoptera and Trichoptera (EPT) in continental European mountain streams, whereas coniferous riparian woody vegetation acts as a dispersion barrier for EPT (Peredo Arce *et al.*, 2022). Furthermore, the research found that the woody vegetation at ten metres and at 30 metres from the stream contributes equally to the increase of landscape connectivity for EPT indicating that the benefits for these invertebrates are not exclusively over the water (Peredo Arce *et al.*, 2022). Other work investigating the effects of riparian woodland buffers on invertebrate diversity in coupled stream-riparian networks in the Zwaim river basin in Belgium, that aquatic macroinvertebrates were strongly influenced by the extent of riparian vegetation in a riparian band upstream (100–300 m) (Forio *et al.*, 2020). Terrestrial spiders and caranids, however were most associated with local riparian attributes.

Hughes (2003) describes how connectivity between patches of floodplain woodland allows the migration of plant and animal species along the river corridor to provide opportunities for gene flow between populations of tree species and for seeds to be dispersed by water downstream. Riparian woodland can form an important refuge and conduit for the movement of many species throughout a catchment (Broadmeadow & Nisbet, 2004). Wormell (1977) reported the rapid colonisation of restored woodland on the Isle of Rhum in Scotland by native flora and invertebrate fauna dispersing from relic fragments of riparian woodland (in Broadmeadow & Nisbet,2004).

GIS-analysis of functional connectivity, suggested that targeting native woodland creation adjacent to patches of ancient woodland will increase core habitat area and functional network size, enabling faster colonisation of woodland species (Burton *et al.*, 2018). Gorge woodlands have particular value as core ecological sites due to their high biodiversity value. Recent modelling approaches, such as circuit theory and individual based modelling, suggest that spatially targeted woodland creation to infill regional ‘bottlenecks’ has the greatest potential to improve species expansion response to climate change but that it is difficult to accommodate multiple species when targeting woodland creation (Burton *et al.*, 2018). A strategy to create small woodland patches adjacent to larger patches of existing woodland, can provide benefit to the widest range of species.

The NERC funded DURESS project led by Cardiff University addressed the role of riparian land use, including native woodland, in upland Welsh catchments and the impact on fisheries. This highlighted the importance the importance of healthy biodiversity for functional resilience. A diverse community structure was a key factor to ensure the provision of this function (Durance *et al.*, 2016).

Genetic diversity[29] of foundation tree species in river woodlands is key to enabling adaptation to climate change, as diversity helps with resistance to pests and tree diseases that are likely to become more prevalent in future with climate change. For example, Wainhouse & Inward (2016) found changes in reproductive rates of insects such as aphids with climate change. It also enables resilience to other aspects of climate change such drought and changing timing of key life stages due to temperature change (Barsoum *et al.*, 2015). Genetic diversity of foundation tree species for river woodlands has been studied in the USA in relation to cottonwoods. This found that genetic diversity is jointly driven by climatic gradients and river networks. The research concluded that: first, gene flow of Fremont cottonwood is jointly controlled by the connectivity of the river network and gradients of

[29] Genetic diversity is one of the aspects covered in this note about how biodiversity affects the ability of woodlands to adapt to climate change Climate change factsheet: Climate change and biodiversity (forestresearch.gov.uk)

seasonal precipitation. Second, gene flow is facilitated by mid-sized to large rivers, and is resisted by small streams and terrestrial uplands, with resistance to gene flow decreasing with river size. Third, genetic differentiation increases with cumulative differences in winter and spring precipitation. The results suggest that ongoing fragmentation of riparian habitats will lead to a loss of landscape-level genetic connectivity, leading to increased inbreeding and the concomitant loss of genetic diversity in a foundation species (Cushman *et al.*, 2014). This highlights the key role of re-stablishing river woodlands to enable genetic diversity, alongside sourcing trees for planting with local provenance to maintain genetics.

3.7.6 Supporting river hydromorphological processes and diversity

Functional processes

Riparian and floodplain woodland and their associated large woody material play a strong role in promoting hydromorphic and geomorphic improvement, morphological diversity and in turn aquatic biodiversity. The influence of riparian plants (including woody species) as river engineers (Gurnell, 2014) that affect the physical context of river channels has been widely documented, reviewed and summarised well by the CONVERGES European review by Gonzalez del Tánago *et al.*, 2021.

Riparian vegetation successively creates and modifies river landforms (Tal and Paola, 2010) (in Gonzalez del Tánago *et al.*, 2021). Canopy and root architecture, along with the spatial distribution of plants, strongly influence flow resistance and the direction of flows. Additionally, vegetation height and density (i.e., “biovolume” of plants) have a great capacity to retain sediment, which can be frequently reinforced by large woody material (Gurnell *et al.*, 2001, 2006; Corenblit *et al.*, 2009b).

Feedbacks between woody plants and fluvial morphodynamics result in co-development of riparian vegetation communities and channel form (Lightbody *et al.*, 2019). Riparian vegetation plays an essential role in influencing channel stability and the quality of the physical habitat for many aquatic communities (Reid *et al.*, 2010; Sievers *et al.*, 2017). Natural river floodplains present a mosaic of habitats generated by fluvial deposition and lateral instability in platform associated with a dynamic flow regime. Such processes lead to the formation of a variety of water bodies or backwaters within the riverscape that are almost lentic in character and play a significant role in maintaining macrophyte diversity (Keruzoré *et al.*, 2013). Kerr & Nisbet (1996) describe how the restoration of floodplain woodland can provide an extension of aquatic habitats in the form of multiple braided river channels, pools and gravel features which can provide an overall benefit to habitat quantity and quality.

The hydromorphological role of riparian vegetation in providing large wood has been deeply studied and demonstrated (Piégay and Gurnell, 1997; Gurnell *et al.*, 2012; Bertoldi *et al.*, 2013), showing the crucial joint impact of riparian woodland and large wood on river channel form and dynamics (Bertoldi *et al.*, 2015; Wohl *et al.*, 2019). Large woody material plays an important functional role in the ecology of streams and rivers by influencing physical, chemical and biological processes within the system (McKenzie, 1996; Abbe & Montgomery, 1996). The large woody material enhances the hydraulic, morphological and structural complexity of naturally functioning river channels, subsequently increasing habitat diversity and availability (Caithness *et al.*, 2020). Large wood material regulates the energy of running water and increases productivity. Log jams and man-made large wood structures provide a stable substrate for aquatic organisms. The woody material including fallen trees and branch litter divert and obstruct the flow which creates a more complex diversity of flow-types and forms pools which are an important habitat for mature fish (see section 3.9.4) and act as refugia for aquatic fauna during periods of low flow (Broadmeadow & Nisbet, 2004).

Large woody material plays an important role in the provision of regeneration sites for floodplain forest species. Wood material deposits create an obstacle to river flow. During periods of high flow, depressions are scoured upstream of the material which become filled with fine sediments creating a moist microsite suitable for the regeneration of pioneer tree species. In addition, plumes of fine sediment are deposited downstream of the woody material forming another type of microsite rich in trapped nutrients, organic matter and seeds. Wood material in channels can function directly as 'nurse logs' with the creation of alluvial islands which provide important sites for seedlings of floodplain forest species to colonise (Hughes, 2003).

Measured effect

Field and laboratory studies have proved that channel morphology and channel changes are strongly linked to the growth and development of riparian vegetation, which control bank erosion and control channel characteristics in multi-thread and single-thread meandering rivers (Tal *et al.*, 2004; Braudrick *et al.*, 2009; Tal and Paola, 2010; Bertoldi *et al.*, 2015).

Pioneer tree species associated with riparian and floodplain woodlands such as willow (Salix species) and poplar (*Populus nigra*) in France have been found to trap and retain sediment leading to an interrelationship between landform and habitat creation over time (Corenblit *et al.*, 2009a, 2009b).

The response of topography and flow to the presence of riparian tree seedlings with contrasting morphologies in an experimental, field-scale, meandering stream channel with a mobile sand bed at the University of Minnesota St. Anthony Falls Laboratory Outdoor StreamLab was measured (Lightbody *et al.*, 2019). On a convex point bar, seedlings of *Tamarix* spp. (tamarisk) and *Populus fremontii* (cottonwood) were installed with intact roots and a bankfull flood, with each of eight runs varying sediment supply, plant density, and plant species was simulated. Vegetation reduced turbulence and velocities on the bar relative to bare-bed conditions, inducing sediment deposition when vegetation was present, regardless of vegetation density or species. Sediment supply also played a dominant role, eliminating sediment supply reduced deposition regardless of the presence of vegetation. Unexpectedly, plant density and species architecture (shrubby tamarisk vs. single-stemmed cottonwood) had only a secondary influence on hydraulics and sediment transport. In the absence of plants, mobile bedforms were prominent across the bar, but vegetation of all types decreased the height and lateral extent of bedforms migrating across the bar, suggesting a mechanism by which vegetation modulates feedbacks among sediment transport, topography, and hydraulics.

The River Gearagh in Southern Ireland has floodplain woodland, good water quality and habitat heterogeneity. It was found to have a high taxon richness of aquatic invertebrates in stable channels (Harper *et al.*, 1997). A New Zealand study of floodplain forest found that the abundance and biomass of brown trout *(Salmo trutta* L.) and the richness and diversity of benthic invertebrates were all significantly greater in willowed (*Salix* spp.) than in non-willowed stream reaches (Glova & Sagar, 1994).

Research at the Eddleston Restoration Project in the Scottish Borders is monitoring relationships between changes in river morphology and aquatic invertebrates with a Before-After-Control-Impact (BACI) monitoring framework, but further work is required to understand the links with tree planting on the floodplain. Initial results from analysing the impact of channel reconfiguration on the benthic macroinvertebrate community in Eddleston Water after seven years (2012-2019) has shown highly significant increases in taxon richness but at both impact and control sites (APEM, 2020). Also, channel reconfiguration caused an abrupt shift in macroinvertebrate community composition from one dominated numerically by mayflies, stoneflies and caddisflies to one dominated by oligochaetes and chironomids, which are rapid colonisers of newly created or freshly disturbed substrates. Further analysis is still required to understand the influence of habitat composition, fine sediment, submergent vegetation and habitat diversity on macroinvertebrate composition and diversity.

The important role of lateral dynamics with the establishment of backwater channels and the benefits they provide to increasing macrophyte biodiversity has been quantified on two relatively undisturbed large upland rivers in Scotland; on the River Tummel and River Tay in Perthshire (Keruzoré *et al.*, 2013). Paired backwater and main channel macrophyte sampling was surveyed over the two growing seasons at five sites per river with six transects per site. Backwaters, despite representing only 5% of the total area of aquatic habitat, supported a significantly higher concentration of species (65% of species recorded at the landscape scale were unique to backwaters) than the main channel. The frequency with which backwaters were connected to the main channel during flood flows influenced their species richness. Highest species richness in backwaters was typically found at low connectivity. Standing crop in backwaters was 150 times higher per unit area than in the main channel, while at the landscape scale backwaters accounted for an average 89% of aquatic plant biomass. The highest plant biomass was found at low and medium connectivity with the main channel. The protection afforded by the SSSI and SAC for alluvial Alderwoods on the River Tay is likely to have helped preserve those features (Iain Sime, *pers. comm*). The results emphasize the importance of river hydrodynamics and lateral connectivity in maintaining macrophyte community diversity along large rivers.

Restoration work in the Scottish Highlands supported by morpho-dynamic modelling has illustrated that wood (i.e. 'large wood structures') are a fundamental feature in the reinstatement of physical processes and channel evolution and subsequently improved habitat availability and diversity (Caithness *et al.*, 2020). On the Aberarder Estate, alternating 'bar-apex' structures were located within a one km reach of the Upper Nairn. The large woody material was composed of root wads, protruding laterally into the channel by ~30% of the active channel width (as guided by the morpho-dynamic modelling). Presence of the wood allowed the channel to rapidly adjust to a 'dynamic pool riffle morphology' characterised by alluvial bars, riffles and pools. Initial monitoring work is showing increases in Atlantic salmon redds and at other Scottish restoration sites involving large woody material, an increase in spawning habitats (see section 3.9.4 on improving habitat for fish).

There is evidence from the Allt Lorgy[30], in the Spey catchment, Scotland that restoring a straightened, canalised stretch of this tributary of the River Dulnain (which was once a wandering gravel-bed river) results in a more diverse in-channel geomorphology (Williams *et al.*, (2020). Once bank protection was removed to allow natural bank erosion and to provide a local supply of sediment, the sediment enabled the formation and maintenance of lateral and point bars, riffles and diagonal bar complexes, and the instream wood created structurally-forced pools and riffles. Results showed restoration increased geomorphic unit diversity, with the Shannon Diversity Index increasing from 1.40 pre-restoration (2012) to 2.04 (2014) and 2.05 (2016) after restoration. Channel widening caused aerial coverage of in-channel geomorphic units to increase 23% after restoration and 6% further in the two-years following restoration.

Research has found that large woody material rapidly restores biodiversity in riverine food webs in chalk streams in England (Thompson *et al.*, 2017). By adopting a Multiple Before-After-Control Impact (MBACI) design, the work successfully demonstrated the positive causal relationships between large woody material introductions, biodiversity restoration and food web responses. Populations of invertebrates and an apex predator, brown trout (*Salmo trutta*), increased, and food web analysis suggested increased biomass flux from basal resources to invertebrates and subsequently fishes within restored reaches.

3.7.7 Factors influencing effectiveness

The design and management of riparian woodlands (natural and man-made) influences the effectiveness of the different functions to deliver biodiversity benefits (as summarised well in

[30] The Allt Lorgy restoration project, winner of the 2020 River Restoration Centre UK River Prize

Broadmeadow & Nisbet, 2004). Native tree species add greatly to the overall biodiversity of conifer forests and are particularly valuable when planted within the riparian zone. The type of tree species planted influences the wildlife that it attracts. Native oak and willow species support the greatest diversity of lichen and invertebrate species, although birch is also very valuable particularly in Scotland. Willow and bird cherry provide good foraging habitat for bats because of the high biomass of terrestrial invertebrates they support.

An intricate mosaic of open ground, occasional large old trees, scrub thicket and closed canopy woodland is often the favoured structure for riparian buffers (Broadmeadow & Nisbet, 2004). Over-mature trees are especially important in providing dead wood and wood material to the stream system. This creates habitat diversity and thus, conservation value. Areas of open ground and light shade are important for maintaining a good cover of aquatic and marginal vegetation, which has an important influence on the benthic invertebrate population. If man-made riparian woodland buffer areas are not managed, then willow and alder scrub can become too dense casting undesirable heavy shade over watercourses. A natural riparian native woodland will self-manage composition and cover. The width of riparian woodland buffers will influence the biodiversity function that it can deliver with a 10-50 metre buffer recommended for invertebrate diversity and a 25-100 metre buffer recommended for leaf litter supply and large woody material (Broadmeadow & Nisbet, 2004).

Different tree species mixes affect morphological processes such as natural rates of erosion and the right native riparian tree species compositions are required to match the climate, hydrology and geology of the catchment and region. The location and design of large woody material in streams and rivers will influence the effectiveness of kick-starting morphological and ecological processes and engineering design models are available to help with appropriate placement in streams to maximise effectiveness of such measures.

The effectiveness of functions to support aquatic and hydromorphological processes and biodiversity (provision of large woody material, leaf litter, temperature moderation) is affected by the width of the riparian woodland buffer. Further tools need to be developed to define optimum functional spatial extents under different river types and catchment characteristics (size, hydrology and land-use-types, etc.).

3.7.8 Evaluation of evidence

Strength of evidence (based on quality of studies)

Supporting aquatic processes: i/Providing a variety of light conditions; ii/ Supporting nutrient cycling and food webs: There is **very strong evidence** from the international literature that include empirical and modelling research that native riparian woodlands play an essential role in regulating good physical, chemical and biological condition of freshwaters which in turn support freshwater biodiversity. Many freshwater ecology textbooks summarise a strong body of empirical evidence of the science which underpin the biophysical processes linking the riparian, aquatic and upland zones.

Supporting other species:
There is **strong** evidence that native riparian woodlands support many other species including ones of conservation concern with strong dependent inter relationships. There is **strong** evidence from the international literature and Scotland that establishing and maintaining woody vegetation in riparian strips in agricultural catchments increases structure diversity and increases abundance and diversity of wildlife at the landscape scale.

Providing habitat connectivity & supporting genetic diversity:
There is **moderate** evidence from observational field studies in Scotland that connectivity of native woodlands aids regeneration. There is modelling evidence to suggest that spatially targeted woodland

creation has the greatest potential to improve species expansion response. There is evidence fromthe international literature that river woodlands are important for maintaining genetic diversity due to their connective nature if present / restored across the landscape.

Supporting river hydromorphological processes and diversity: There is **very strong** evidence from field studies from the international literature that underpins the importance of native riparian and floodplain woodlands and their associated large woody material in key hydrological, hydro-morphological and biological processes. There is **strong** evidence supported by BACI design that large woody material rapidly restores biodiversity in riverine food webs in England. There is strong evidence from Scotland that the re-instatement of natural morphological processes leads to greater geomorphic unit diversity aided by large woody material. Although there is less quantified data for freshwater ecology benefits, monitoring has begun and observational studies are showing positive results from habitats created from large woody material for fish. In addition, morphological processes creating backwaters on the River Tay associated with the alluvial woodlands provides a **strong** case-control study showing significant benefits to macrophyte diversity.

Limitations & Gaps in Research

A greater number of studies have begun to consider biodiversity in relation to other types of woodland in recent years, but there is a lack of controlled, field-based evidence for the effect of native woodland expansion on biodiversity (Burton *et al*., 2018). Most evidence for native woodland is derived from reviews, landscape scale GIS or modelling methodologies, primarily focusing on the potential for increasing woodland connectivity to enhance biodiversity at the landscape scale. This would suggest that the riparian woodland sub-set is even smaller.

Indicators for biodiversity of riparian zones need to use more than one indicator as ecosystem relationships are complex as found in studies of vegetation patterns in non-buffered, buffered and native riparian woodland margins in Northeast Scotland.

There is a need to identify a suitable focal species model for river woodland habitat; bird or bat/FWPM or aquatic invertebrate/lichen.

There is a need for improved understanding of genetic diversity of foundation river woodland species in Scotland, and the implications for sourcing trees for re-establishment of river woodlands.

There is limited quantified evidence of the role of river woodlands in supporting macroinvertebrates in Scotland and further long-term monitoring at restoration sites is required.

There is a need for further maps of riparian and floodplain woodland (to include structure and composition) for different regions and catchments in Scotland. There is an aspiration to better map and display the occurrence of alluvial woodlands (whether or not it is in a SAC) on the Habitat Map of Scotland. [31].

Research has been undertaken in Spain to identify the right native riparian tree species in specific catchments and regions to help support natural banks with natural rates of erosion (mitigating land loss for agriculture) but also for the wider purpose of restoring healthier riparian corridors. The work involved a national inventory of riparian vegetation (Lara *et al*., 2007, 2012), regionalisation of riparian vegetation for species selection (Magdaleno & Martinez, 2013) and the development of a Riparian Forest Evaluation Index to assess the condition of riparian forest vegetation (Magdaleno & Martinez, 2014). Similar research, like this, is still outstanding in Scotland. Based on the national map of riparian

[31] https://www.nature.scot/landscapes-and-habitats/habitat-map-scotland

woodland, tree nurseries for different tree species of riparian and floodplain woodlands should be set up to fulfil the need of future tree planting and river restoration projects and this should adhere to legislation in the EU Directive 1999/105/CE.

Further work is required on the impact and land required to accommodate rewilding. This includes understanding the interactions of large herbivores such as beavers and deer on river woodlands, their impact on riparian woodlands including ecosystem consequences and delivery of benefits. More empirical research is required particularly on the scaling and magnitude of beaver activity effects (Geris *et al.*, 2022). This needs to be supported by long-term experimental monitoring in Scotland and modelling.

There is published guidance on the width of riparian woodland buffer required depending on the function desired (large woody material and leaf litter supply, temperature moderation, invertebrate diversity) (Broadmeadow & Nisbet, 2004). However, there is no automated tool available, to identify the spatial extent of the functional riparian buffer area.

Any new tool developed to define the functional riparian zone will require local ground truthing. Increased availability and resolution of remote sensing data will provide potential scope for improvement.

Further research and development on SEPA's GIS analysis tool for determining space for morphological dynamic (including riparian vegetation width) is required. This should include validation of the sections identified by the GIS tool on site that allow for the prioritisation of reaches under different criteria.

More research is required to further our understanding of landscape-scale nutrient recycling and to quantify the benefits that river and riparian species play within this (including fish).

3.8 Good human health

3.8.1 Overview of benefit

Woodlands can provide health benefits to people who visit this natural environment. The benefits of cooling and shading provided by trees could also reduce the incidence (especially in summer) of heat stroke and other heat-related health problems. Many cities and towns experience higher air temperatures than surrounding rural areas (urban heat island effect). In light of climate change, the need for cooling by trees and greenspaces is expected to increase even in temperate climates such as that of the UK, with heatwaves forecast to become more frequent and severe in future decades (Monteiro *et al.*, 2019).

The combined exposure to both integrated wooded green blue spaces provided by river woodlands has the potential to be very powerful especially in urban environments. Scotland faces a large number of health and social challenges such as obesity, mental health problems, cardio- vascular diseases, Type 2 diabetes and social exclusion. Many such illnesses are linked to chronic stress and other lifestyle factors, such as insufficient physical activity. These health problems disproportionally affect socio-economically disadvantaged and vulnerable groups and add pressure to already overstretched healthcare budgets. There is a need for a stronger focus on the use and the creation of health-promoting environments that allow exposure and encourage healthy living and working, physical activity and active transport, including at places of work, hospitals and nursing homes. Doctors throughout the world are prescribing spending time in nature and New Zealand has long boasted a green prescription scheme (Li, 2018). There is also now a focus on green social prescribing in England[32].

[32] For green social prescribing in England, see: NHS England » Green social prescribing

Although NHS Scotland has not quite moved towards a standard for prescribing, there is gradually more recognition of social prescribing, supported by NHS campaigns such as Think Health, Think Nature.

This section reviews the evidence on health benefits provided by trees (with reference to river woodland types where the information is available) under two main functions of providing nature for human exposure with integrated blue-green spaces and cooling air in summer and reducing ultraviolet radiation through shading, detailing the specific health benefits under each.

Beneficiaries

The NHS and healthcare providers will benefit from improvements in people's physical and mental health from being exposed to wooded green blue spaces. This includes at hospitals, care homes and nursing home settings with residents benefiting from exposure even from inside. A good example of this in Scotland is the work of the green exercise partnership in its demonstration projects across a number of hospitals[33]. All businesses that employ people will also benefit along with educational and recreational services with more people in attendance. Local Authorities which are involved in green infrastructure planning and development should embrace greenspace design and tree placement that facilitate cooling and shading.

3.8.2 Exposing people to nature for human health: integrated blue green spaces

Functional processes

The contribution to human health and well-being from exposing people to nature is increasingly understood within science. This includes physical exposure to woodland environments. The sensory elements of a forest (sounds, scent, light) give humans a sense of comfort which eases stress and anxiety and makes us think more clearly (Li, 2018). Being in nature can restore our mood, give us back our energy and vitality, refresh and rejuvenate us. There are physical elements within the forest which cause this effect. As well as having a higher concentration of oxygen, the air in forests have natural oils called phytoncides which are a part of the tree's defence system and exposure to them in medical trials have shown a variety of health benefits including decreasing levels of stress hormones and levels of anxiety (Li, 2018). There are many more negative ions in the outdoor air environment than indoors and they are particularly abundant in forests and near waterfalls, rivers and streams. These ions are linked to energizing and refreshing effects and help increase mental clarity and our sense of well-being (Li, 2018).

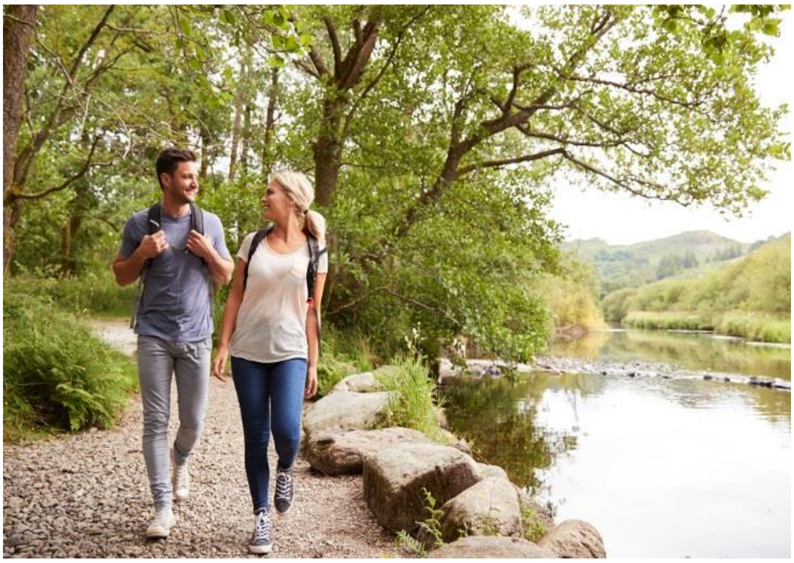
Measured effect

A study led by a team of authors from the FOREST EUROPE Expert group on Human Health and well-being has been done which includes a comprehensive scientific review of empirical evidence of health benefits provided by woodlands (Marušáková & Sallmannshofer, 2019). In the literature, five key mechanisms for the health benefits of forests have been identified and discussed within the research field:

i. Reduced exposure to noises and air pollution (see section 3.5.1)
ii. Stress reduction and psychological and physiological restoration
iii. Strengthening the immune system through contact with nature
iv. Increased physical activity and reduction in obesity rates
v. Better social contacts.

[33] NHS Greenspace | NatureScot

The results from this review and other studies show a positive measured effect of woodlands on human health. The review by Marušáková & Sallmannshofer (2019) found that there is strong evidence that forest visits have a positive impact on mental health including reduction in risk to stress and attention fatigue. Walking in natural settings with trees versus urban settings has been shown to have a positive impact on brain functioning which controls depression, reducing negative thoughts (Bratman *et al.*, 2015). There is also increasing evidence that visits to forest environments have positive physiological effects such as lower blood pressure and pulse rate, reduced cortisol levels and suppressed nervous activity (Marušáková & Sallmannshofer, 2019). Positive effects of forest bathing on people suffering from Post Traumatic Stress Disorder or experiencing stress has been proven as well as on people suffering from psychotic disorders (Bielinis *et al.*, 2020). The immune system can be strengthened through contact with nature and soil micro-organisms and natural tree defence oils or phytoncides (Li, 2018). Studies have shown that children living in rural areas are less susceptible to allergies than children living in urban areas. 3-carene, a phytoncide from pine trees has been shown to have a sleep enhancing effect by targeting brain receptors (Woo *et al.*, 2019). Forest and woodland environments strengthen social relationships with studies showing increased positive social behaviours amongst children and positive impact of mental well-being. A study in the Netherlands found that less greenspace coincided with a perceived lack of social support and feelings of loneliness (Marušáková & Sallmannshofer, 2019). A study involving a cohort of 3,568 adolescents aged nine to 15 years at 31 schools across London found that a higher daily exposure to woodland, but not grassland, was associated with higher scores for cognitive development and a lower risk of emotional and behavioural problems for adolescents (Maes *et al.,* 2021).



Walking in natural settings with trees versus urban settings has been shown to have a positive impact on brain functioning which controls depression, reducing negative thoughts

The health benefits of blue space including rivers lakes and the sea has received less attention than green space. The balance of evidence suggested a positive association between greater exposure to outdoor blue spaces and benefits to mental health and well-being and levels of physical activity. The evidence of an association between outdoor blue space exposure and general health, obesity and cardiovascular and related outcomes was less consistent (Gascon M *et al.*, 2017). The EKLIPSE Expert Working Group on Biodiversity and Mental Health undertook a systematic review of the types and characteristics of urban and peri-urban blue spaces having an impact on human mental health and wellbeing (Beute *et al.*, 2020). The main focus of this review was on mental health effects of blue space. Few studies investigated inland water exposure, looking at either a river, a canal, a wetland, or at the percentage of freshwater around the residence. It appeared that positive associations with mental health were less clear for inland waters than coastal blue space. The systematic review showed that there is a lack of high-quality peer-reviewed papers on the topic. The main conclusion of the systematic review is that in this relatively young field of research more high-quality research is necessary, including a focus on a wider range of blue space (particularly inland water) types, blue space characteristics, and geographical locations (especially beyond the United Kingdom). More research is underway across Europe to better understand relationships with specific types of blue spaces through the Blue health project[34] funded by Horizon 2020.

Although the health benefits of river woodlands have not been quantified, the evidence from research on health benefits from green space with trees and blue space does suggest that a positive effect is highly likely and especially with the co-benefits of exposure to an integrated blue-green environment.

Factors influencing effectiveness

The design and location of river woodlands are likely to have an influence on the level of provision of health benefits. Studies in Europe and the US have shown that the quality of vegetation and size of nature areas matters with larger forested areas with more clean air, tranquillity, space and biodiversity having greater positive physiological effects.

Studies have reported that living in proximity to green areas increases the likelihood of frequent exercise. The UK's Parliamentary Office of Science and Technology (POST, 2016) reviewed whether proximity to green space, quality and accessibility influence physical activity. This showed that those living closer to green space were more likely to use it, and more frequently. A study in the UK also found that people who live within 500 metres of accessible green space are 24% more likely to meet 30 minutes of exercise levels of physical activity (Natural England, 2011) People are likely to be more active in urban areas with good quality, well connected and local green areas. Riparian woodland networks can provide this and the network links between other green and blue spaces.

The time exposed to nature influences the effectiveness of woodland measures to provide health benefits. There is evidence from the UK that suggest that spending 120 minutes a week in nature is associated with good health and wellbeing (White *et al.*,2019).

3.8.3 Cooling air in summer & reducing ultraviolet radiation

Functional processes

Trees and greenspaces in urban areas can provide cooling and shading on hot days which could reduce risks of heat stroke, lack of sleep and discomfort (and especially during active travel or during recreational activities). Trees can also provide shading from harmful ultraviolet (UV) radiation which could be expected to reduce eye cataracts and morbidity and mortality from skin cancer (Saraev, 2011).

Human Thermal Comfort (HTC) and whether a person experiences heat stress is influenced by air temperature (Ta), humidity, wind speed and mean radiant temperature (Tmrt) (Coutts & Tapper, 2017). The higher the temperatures of objects around (such as the ground and walls) the greater the radiant heat received by the body. During the day under warm sunny conditions, Tmrt is the most important environmental variable influencing HTC. Therefore, providing shade to block solar radiation and to reduce the temperature of urban surfaces is critical.

Trees and other vegetation help cool cities by evapotranspiration, reflection and lower heat storage (Montiero *et al.*, 2019). Through the process of evapotranspiration, some of the energy absorbed by trees evaporates water within their leaves, cooling them. The resultant water vapour is then transpired through the leaf pores (stomata) into the air without warming the air around them. Vegetated areas such as provided by trees and woodlands typically reflect more solar radiation away from the surface than dark, artificial surfaces. Consequently, less solar radiation will be absorbed, resulting in vegetated areas having cooler surfaces and lower air temperatures compared with built-

[34] https://bluehealth2020.eu/about/

up, non-vegetated areas. Trees and their associated understorey vegetation will have lower heat storage capacities than many artificial materials and transfer energy rapidly to the air because of their multiple small leaves and branches which facilitate air movement.

Measured effect

A number of studies have quantified the cooling effect of trees in temperate climates (as reviewed and summarised by Monteiro *et al.*, 2019). Modelling studies in Greater Manchester, UK, showed differences in maximum surface temperature in summer of around 12°C between built environments (e.g. town centres) and greenspace areas (woodlands) (Gill *et al.*, 2007). A 10% increase in tree canopy cover was predicted to result in a 3–4 °C decrease in ambient temperature. Monitoring of daytime air temperatures in and around 62 urban parks and forests in Leipzig, Germany, has shown that the cooling effect of urban forests is higher than urban parks (an average of 0.8 °C for forests and 0.5 °C for parks) (Jaganmohan *et al.*, 2016).

Soil surface temperatures across the mid-sized UK city of Leicester have been measured by burying temperature loggers at the surface of greenspace soils at 100 sites including sites with trees and shrubs (Edmondson *et al.*, 2016). In the non-domestic green spaces the effects of woody vegetation were most apparent during the summer months, when average soil temperature beneath herbaceous vegetation was more than 3 °C higher than beneath trees and shrubs; 17.2 and 14.1 °C respectively. The largest effects were on summer mean maximum daily temperatures which ranged from 20.9 °C in the non-domestic herbaceous greenspace to 15.2 °C under trees and shrubs in the same land-use category, a decrease of 5.7 °C. On many days maximum temperatures in grasslands exceeded 30 °C, whereas this temperature was never reached under woody vegetation in non-domestic greenspaces. In domestic gardens the overall effects of trees and shrubs decreased maximum temperatures on average by only 2.2 °C.

There is no research that specifically looks at the interaction between the river and trees in the urban riparian zone on the cooling effect. There are some studies that have looked at the interaction of rivers and vegetation in general. A study in Sheffield found cooling from the river is shown to vary with ambient air temperature, with greater cooling found at higher ambient air temperatures at all sites. When air temperatures were > 20 °C, the change in surface temperature was −1 °C at the river, showing a one degree difference. The level of cooling on the riverbank was affected significantly by the local urban form with greatest cooling found on highly vegetated banks. (Hathway & Sharples, 2012).

Evidence to quantify a positive effect of cooling air in summer by trees on health outcomes is limited. One UK case study identified was undertaken in Gateshead (north-east England) and is a study of urban residents' perceptions of benefits of green areas (urban parks) during heat waves (Lafortezza *et al.*, 2009). Based on survey responses (n = 400), the study showed that longer and more frequent visits to greenspaces generate significant improvements in the perceived benefits and well-being of users and alleviate discomfort of extreme heat (in the review of the health benefits of street trees, Saraev, 2011).

One study, in the Norwegian city of Oslo (Venter, *et al.*, 2019), integrated spatial measures of urban surface temperatures, tree canopy cover and population demographics to model the potential risk of heat exposure in Oslo city without trees. The modelled surface temperature changes suggest that each tree in the city mitigates the potential risk of heat exposure for approximately one heat-sensitive person (75 years or older) by one day. The approach goes beyond traditional urban heat island modelling by spatially-explicit modelling of an ecosystem services indicator linked to human health benefits. The methods presented are generally replicable in other European cities.

In the continental USA, where more extreme summer temperatures are experienced than are typical in the UK, one study quantified, through modelling, the impact that typical urban heat island mitigation strategies, such as reflective roofs and vegetation, could have on weather conditions and estimated mortality during extreme heat event, in the cities of Baltimore, Los Angeles and New York (Vanos, *et al*. 2014). Examples of the mitigation strategies considered include use of green roofs, shade trees, and vegetation, as well as surfaces that reflect sunlight rather than absorb it as heat. The study found that use of vegetation was likely to be as effective as use of reflective surfaces for mitigating urban heat island effects and such strategies could save up to 32 lives in Baltimore, 22 lives in Los Angeles, and 219 lives in New York over a 10-year period. Although river woodlands were not specifically included, the important cooling role of trees in urban areas through shade and evapotranspiration was cited.

Factors influencing effectiveness

The comprehensive Forest Research review by Montiero *et al*., (2019) summarises factors which influence the effectiveness of trees in reducing air temperatures (see review for more detail).

The design and location of woodlands are key factors including the size of the greenspace. In London and Germany, larger greenspaces have been found to provide more cooling than smaller ones and cooling effects from the largest woodlands and parks in Germany have been found to extend up to 470 m from their boundaries-(Jaganmohan *et al*., 2016). When considering blue space as well, it has been found in China that the wider the river, the farther the cooling distance extends (Du *et al*., 2016). In the Sheffield study of a medium sized river the influence of the river and riparian vegetation extended 30 m from the riverbank, and opening up streets to the river enables propagation of the cooler air (Hathway & Sharples, 2012).

The type of tree species, their shape and density and woodland groundcover will influence the cooling effect. Tree species have different inherent characteristics that control their growth, form, physiology and radiative properties, and lead to some species having greater potential to provide cooling than others. Trees greatly reduce UV irradiance in their shade when they obscure both the sun and sky. Forested areas with closed tree canopies provide nearly total protection and more protection is provided by larger canopies often associated with larger trees (Saraev, 2011).

There is guidance available on design criteria and strategies to maximise cooling effects from trees with optimised tree placements (Monterio *et al*., 2019; Coutts & Tapper, 2017[35]). However there is a need for ongoing research to understand how best to design urban blue-green infrastructure involving river woodland types within the riparian zone.

3.8.4 Evaluation of evidence

Strength in evidence (quality of studies)

Exposing people to nature: integrated blue green space: The biophysical processes which underpin the health benefits from exposure to trees and woods are increasingly understood within science. There is **strong** quantified evidence of a positive effect on health from being exposed to woodlands with **moderate** evidence for water and rivers but further research is underway. Although direct health benefits from river woodlands have not been quantified, a positive effect is likely.

Cooling air in summer & reducing ultraviolet radiation:

The biophysical processes in which trees cool air temperatures are well known. There is **strong** quantified evidence that trees and woodlands and water have a cooling effect and this cooling effect increases with the size of blue and greenspace. There is limited evidence which directly measures the

[35] Trees for a Cool City: Guidelines for optimised tree placement. Melbourne Australia: Cooperative Research Centre for Water Sensitive Cities

effect of health benefits from trees (such as reducing heat stress, lack of sleep and discomfort) but modelling results indicate a reduction in the risk of heat exposure and mortality in extremes of heat with greenspace including trees, so a positive contribution is likely.

Limitations and Gaps in Research

There are many more peer-reviewed publications analysing the effect of greenspace than studies focusing exclusively on forests or woodland or river woodlands. The health benefits, however, are likely to be universal and not affected by type but more by extent, condition and accessibility.

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.

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 (Bowditch E. Per Comm.)

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.

Further research is required to understand how best to design urban blue-green infrastructure involving river woodland types to optimise cooling for health benefits.

Further research is needed to understand the impact of wooded riparian zones in Scottish cities on the urban heat island effect and health benefits.

3.9 Wild fish and angling

3.9.1 Overview of benefit

River woodlands enable fish species that are adapted to cool water to continue to survive and flourish under climate change by providing cool water refuges under summer temperature extremes. River woodlands also provide food and diverse habitats for fish. Large woody material in the channel can create a complex diversity of habitats including pools, riffles and glides that support the varying habitat requirements of different species and life stages. The roots of riparian woodland trees which are submerged in water also provide cover and important refuges from predators.

Atlantic salmon (*Salmon salar*), brown trout (*Salmon trutta*) and Arctic charr found in Scotland are adapted to cool water environments and their populations are already being subtly affected by climate change. This includes changes in age of Atlantic salmon smolting, which has been shown to be linked to shifts in temperature regime (Gurney *et al.*, 2008). Juvenile salmonids typically perform best where temperatures are in the mid-teens and struggle when temperatures exceed 20°C with most stages of their lifecycles sensitive to rising temperatures (Solomon & Lightfoot, 2008). Consistent with observations across the world, long-term temperature data show that river temperatures are rising in Scottish rivers (e.g. Pohle *et al.*, 2019) and there are concerns over the future of suitable thermal habitat. The summer of 2018 was the joint hottest on record in Scotland. During this time, ca. 70% of Scottish rivers experienced temperatures that cause thermal stress in Atlantic salmon (>23°C), while some rivers recorded temperatures of 30°C (Jackson *et al.*, 2020), which is at the instantaneous lethal limit for brown trout and close to the limit for juvenile Atlantic salmon (33°C) (Elliot & Elliot, 1995).

UKCP18 climate change projections suggest summers as hot as 2018 could occur every other year by 2050[36].

Alongside the management of flow regulation and abstractions, riparian planting is the primary climate change mitigation option being considered by fisheries and river managers in Scotland (Jackson *et al.*, 2018). For example, the River Dee Trust's *Million Trees to Save Our Salmon* Restoration Project is part of a £5.5 million project to tackle the decline in salmonid numbers by providing shade on tributaries of the Dee in the Balmoral and Invercauld Estates.

This section focuses on the evidence relating to how trees can support wild fish and angling under the main functions of regulating local climate through shading, providing food for fish and improving habitat for fish with large woody material.

Beneficiaries

There are a wide range of beneficiaries from river woodland restoration for wild fish and angling, including fisheries and river managers in Scotland, estate owners, anglers, rural businesses, and tourism businesses such as accommodation providers.

3.9.2 Regulating local climate through shading

Functional processes

An understanding of the thermal biology of freshwater fish in combination with thermal dynamics and heat exchange processes are required to understand and analyse the potential effect of river woodlands on moderating stream temperatures and providing benefits to fish at different times of the year.

The lifecycle stages[37] of Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*) (important cold water fish species found in Scotland) are temperature dependent and increases in water temperature outside threshold ranges will have a negative effect on reproduction, growth and survival rates (Solomon & Lightfoot, 2008; Elliot & Elliot, 2010; Jonsson & Jonsson, 2011). The optimal mean daily water temperature for juvenile Atlantic salmon growth is ca. 16°C where food is unlimited, but lower where resources are constrained (Gurney *et al.*, 2008). Where mean daily temperatures exceed 23°C juvenile Atlantic salmon stop growing. Where maximum daily temperatures exceed ca. 23°C juvenile Atlantic salmon begin to exhibit thermal stress and show behavioural change (Breau, 2011). Where maximum daily temperatures exceed ca. 33°C juvenile Atlantic salmon experience mortality. In adult Atlantic salmon, mortality from catch and release fisheries is increased where minimum night-time temperatures exceed 20°C. Brown trout have similar thermal requirements to salmon, although these tend to be a couple of degrees cooler. Mortality can occur at lower temperatures than these due to a

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[36] Marine Scotland Topic Sheet No. 143 summer-2018-river-tempratures.pdf (www.gov.scot)

[37] For Atlantic salmon, spawning usually occur in winter (Nov-Feb), females lay their eggs in gravel depressions known as redds. The time taken for eggs to hatch depends on ambient water temperature. Hatching usually occurs in early spring. Young fish which still have a defined yolk sac are called alevins. These young fish feed on the yolk sac whilst living within their gravel nest. They emerge form gravel in April or May as fry and develop into parr which will live in the river for 2-3 years depending on the water temperature and food availability. Prior to leaving freshwaters and in order to allow them to survive in marine environments, parr undergo a number of physiological changes as they transform into smolts. The smolts, which are now silver in colour and developing the ability to osmoregulate in sea water, leave rivers for the sea in late spring and are gone by June. Atlantic salmon that return to Scottish rivers from January to June are called spring salmon but in Scotland they can enter rivers at any time of year. Brown trout has two lifecycle patterns- sea trout and freshwater trout. The sea trout life-cycle is similar to Atlantic salmon; spawning in mid Oct to January and emerge from gravel in mid-March, early May.

combination of other factors linked to higher water temperatures such as increased algal growth, leading to depleted night-time dissolved oxygen levels and overcrowding of pools. The salmonid egg stage during winter is the most vulnerable life stage to any increase in temperature as a result of climate change but evidence suggests that woodland measures to moderate river temperatures will be restricted to late spring and summer seasons.

Feld *et al.*, (2018) concluded, in systematic review work, that buffer cooling effects on water temperature, at least in summer, is related to the presence of tree cover. A three-year study on three streams in the New Forest in southern England showed how shade (20-40%) from riparian woodland can prevent water temperatures exceeding lethal limits for brown trout (Broadmeadow *et al.*, 2010).

Dugdale *et al.*, (2018) found that stream temperature responses to bankside vegetation does depend on the type of vegetation present, and net energy fluxes were lower in semi-natural deciduous woodland compared to open grassland.

Inter-annual variability in the effects of riparian woodland on micro-climate, energy exchanges and water temperature have been studied in Scotland. Data was continuously collected over seven years from two reaches of the Girnock Burn (a tributary of the Dee River in Aberdeenshire, Scotland) with contrasting land-use characteristics of semi-natural riparian forest and open moorland. Results found that spring and summer water temperature was typically cooler in the forest and characterised by less inter-annual variability due to reduced, more inter-annually stable energy gain in the forested reach compared to open moorland (Garner *et al.*, 2014).

Process-based flow and temperature models have been integrated to assess the effects of riparian management on high stream water temperatures that could affect juvenile Atlantic salmon in Scotland (Fabris *et al.*, 2018). Results showed that by decreasing both the warming (daylight hours) and the cooling (night-time hours) rates, forest cover leads to a reduction of the temperature range (with a delay of the time to peak by up to two hours) and can therefore be effectively used to moderate projected climate change effects.

The results from a simulation experiment with the application of a deterministic net radiation model parameterised with field data from the Girnock Burn shows that riparian vegetation density, channel orientation and water velocity interact to influence water temperature (Garner *et al.*, 2017).
Simulations were performed under low and high water velocity scenarios. Both velocity scenarios yielded decreases in mean (≥1.6 °C) and maximum (≥3.0 °C) temperature as canopy density increased. Slow-flowing water resided longer within the reach, which enhanced heat accumulation and dissipation, and drove higher maximum and lower minimum temperatures. Garner *et al.*, (2017) demonstrate that, in many reaches, relatively sparse but strategically located vegetation could produce substantial reductions in maximum temperature.

Garner *et al.*, (2014) found that the effect of riparian vegetation on autumn and winter water temperature dynamics was less clear because of the confounding effects of reach-scale inflows of thermally stable groundwater in the moorland reach, which strongly influenced the local heat budget. During the winter, riparian woodland can increase temperatures relative to more open land uses by reducing net longwave and latent (evaporation) heat losses from the river surface (Dugdale *et al.*, 2018). In the winter, altering winter temperatures is made more challenging as water volumes tend to be very high and atmospheric energy exchange is low (Leach & Moore, 2014).

When assessing shading effects from trees on cooling water temperatures, it is also important to assess upstream sources of heat. Longitudinal cooling gradients have been observed during the daytime for stream reaches shaded by coniferous trees downstream of clear cuts or deciduous woodland downstream of open moorland. Modelling work with quantified data from the Girnock Burn has shown that temperature gradients were not generated by cooling of stream water but rather by a combination of reduced rates of heating in the woodland reach and transfer of cooler (overnight and early morning) water from the upstream moorland catchment (Garner *et al.*, (2014). Thus, observed temperatures are controlled by a combination of temperatures from upstream open reaches and lower rates of temperature increase within the forest.

Measured effect

Melcher *et al.*, (2016) (in Feld *et al.*, 2018) observed consistent beneficial effects of riparian shade on water temperature and fish community composition in two headwater streams, containing brown trout (in Feld *et al.*, 2018).

Extensive observational studies and projections using modelling has been undertaken on the Girnock and Baddoch Burns, tributaries of the River Dee catchment in Scotland, to investigate relationships between shade, temperature and salmonids and freshwater macroinvertebrates (e.g. Malcolm *et al.* 2008; Garner *et al.* 2014, 2017; Fabris *et al*. 2018; Dugdale *et al.* 2018, 2019). Differences in juvenile Atlantic fish performances between forested and moorland sites have been found, although the relationships were complex and could be largely related to density and local competition rather than the effects of woodland on food availability or temperature (Malcolm *et al.*, 2008; Garner *et al.*, 2014).

There are very few studies in Scotland that have sufficient data to identify whether riparian woodlands have an overall net benefit to fish populations over other land-use types. The most powerful available study (Malcolm *et al.*, 2019) relates to Atlantic salmon only. This study showed no significant effect of broadleaf / mixed riparian woodland on juvenile Atlantic salmon abundance, but a highly significant negative effect of % conifer woodland (probably influenced by effects of commercial forestry) with fewer Atlantic salmon. This large scale regression study using all available multi-pass electrofishing data collected over ca. 20 years suggests that the overall effect of woodland on Atlantic salmon abundance in Scotland under the current climate is not markedly better than other land uses e.g. open moorland. It also suggests that some forms of riparian woodland (i.e. conifer plantations) could detrimentally affect Atlantic salmon numbers. In some catchments, extensive conifer planting on sites with acidic soils can indirectly lead to acidification of rivers and dense conifer plantations close to the bank can cast heavy shade leading to bare streams banks and beds and high rates of sedimentation (Nisbet *et al.*, 2011).

The relationships between woodland and abundance of Atlantic salmon (and potentially other fish species) are not straight forward. It is complicated by the fact that Scotland has not yet seen the extreme temperatures required for data on its long term effects on salmonids to be measured, analysed and published. Scotland also is restricted by the paucity of research sites with mature extensive native riparian woodland corridors. However, in recent years, there has been a trend towards higher, and in some cases, record summer temperatures and it is known that higher temperatures increase the risk of fish mortality. In Canada, where very high river temperatures are routinely seen, more detailed empirical studies have been carried out. For example, a Passive Integrated Transponder (PIT) telemetry study to investigate the main stem movement behaviour of thermally stressed Atlantic salmon parr in a temperature-impacted river indicates that the fish make reach-scale movements in search of cool water prior to aggregating (Dugdale *et al.*, 2015). There are active discussions on how to maintain and increase thermal refugia in rivers for cold-water fish in Canada which includes the provision of riparian shade (Kurylyk *et al.*, 2015). This also includes the need for greater recognition of the importance of taking into account the availability of ground-water-sourced thermal refugia in the wider catchment.

Modelling work which has been undertaken in North American which assesses the impact of riparian vegetation management on future thermal habitat requirements for Pacific salmon and native trout species under warming climate scenarios and riparian conditions (Spanjer *et al.*, 2022). This work has provided a useful spatially explicit modelling framework that fisheries and catchment managers can use to make decisions regarding riparian vegetation management and its mechanistic impact on water temperature and the survival of juvenile fish. Under the current thermal regime, bioenergetics modelling predicts that juvenile fish lose weight in the lower part of the Quinault river in Washington State; this loss of potential growth worsens by an average of 20–83% in the lower river by 2080, increasing with the loss of riparian shading (Spanjer *et al.*, 2022).

Factors influencing effectiveness

The design and location (or positioning) of riparian woodland are important factors influencing the effectiveness of shade to regulate water temperatures. Riparian woodland buffer width and length effects the magnitude of effect on regulating water temperature. A buffer width of 20 m on either side of the riverbank has been found to be sufficient to keep water temperature within 2°C of a fully forested watershed, while 30 m wide buffers on either side are required for full protection from measurable temperature increases (in Feld *et al.*, 2018). Riparian tree harvesting along stretches of 185 m-810 m lengths of alpine headwater streams led to an increase of 4-6°C in water temperature (Macdonald *et al.*, 2003) (in Feld *et al.*, 2018). Based on modelling studies, Parkyn *et al.* (2003) concluded that at least 1-5 km of shaded stream length was required for first-order streams and 10-20 km for fifth-order streams to reduce water temperature to reference conditions (in Feld *et al.*, 2018). Planting non-native conifers in floodplains or adjacent to rivers can have adverse impacts and planting the right species in the right place will be important to optimise benefits (see best practice guidance[38] and Annex 2 for further details on design including species considerations).

Woodland vegetation on southern banks of slow-flowing waters can create and maintain cool water refugia when water in the unshaded reaches becomes too warm (Garner *et al.*, 2017). The shape of the canopy (including height) will affect levels of shading on different aspects and drone tools have been developed to incorporate this data into models to optimise positioning of planting regimes (Dugdale *et al.*, 2019). Thermal damping by riparian vegetation has been found to be most effective in streams <5 m wide and at shading levels within 50-80% which points at stream width and buffer density as key controls of riparian shade and water temperature (Feld *et al.*, 2018). For tree age, evidence suggests that mature riparian vegetation is required to maximise thermal damping (Feld *et al.*, 2018). Most studies report a cooling effect linked to the width of riparian wooded vegetation and length is important too (see measured effects above). The width-length function of shading effects could help estimate required buffer width-length combinations to limit the maximum summer water temperatures (illustrated in Broadmeadow & Nisbet, 2004).

The Scotland River Temperature Monitoring Network (SRTMN) managed by Marine Scotland was established in response to an evidence gap on river temperatures and the need to establish a national monitoring network. It is a strategic network of more than 220 river temperature dataloggers that allows Marine Scotland to understand how and why river temperatures vary across Scotland, and whether temperatures are changing over time. Data from the network has been used to develop statistical river temperature models that can be used to predict temperatures across all of the Atlantic salmon rivers in Scotland (Marine Scotland, 2018). These models can be used to produce maps that identify where rivers are hottest and most sensitive to climate change. In 2021, Marine Scotland developed a new process-based model to understand and predict where riparian tree planting has the greatest effect on summer maximum river temperatures (Jackson *et al.*, 2021). This model simulated interactions between solar radiation, river order (as a proxy for water volume and residence

[38] Keeping Rivers Cool: A Guidance Manual. Creating riparian shade for climate change adaptation

time), channel width, channel orientation, aspect and tree height to investigate the effects of tree planting on river temperature. The outputs of the models were then used to make predictions and map the effectiveness of tree planting for reducing summer river temperatures.
Taken together, the outputs of SRTMN statistical and process-based models can be used to produce maps[39] to prioritise tree planting where rivers are hottest, most sensitive to climate change and where trees can have a substantial effect in reducing maximum summer river temperatures.

3.9.3 Providing food for fish

Functional processes

McKenzie (1996) describes how a great many invertebrates fall into rivers and streams from the canopies of overhanging riparian trees. Mason *et al.*, (1982) also calculated that streams with a broadleaved woodland canopy can receive four times as many invertebrates compared with a stream without trees. These terrestrial invertebrates, originating from riparian woods (as well as the nutrients contained within leaves and wood itself) provide organic inputs to freshwater systems (Cole *et al.*, 2020), which may increase the abundance of aquatic macroinvertebrates (Malmqvist, 2002; Poole *et al.*, 2013). Increased secondary production may also contribute to increasing feeding opportunities for fish (Nakano & Murakami, 2001). Cole *et al.*, (2020) also describe how the greatest benefits are derived from allochthonous contributions from deciduous woodlands, where receiving waters tend to support higher aquatic invertebrate biomass than waters which receive allochthonous contributions from coniferous plantations (Thomas *et al.*, 2016).

Measured effect

There is evidence from the international literature which shows that terrestrial invertebrates can make up a substantial portion of the summer diet of salmonids. In a study in upland streams in County Mayo, Republic of Ireland, Dineen *et al.* (2007) compared prey intake by Atlantic salmon *Salmo salar* and brown trout *Salmo trutta* across different riparian vegetation types: grassland, open canopy deciduous and closed canopy deciduous. Although aquatic invertebrates dominated prey numbers in the diets of 0+ year Atlantic salmon and brown trout and 1+ year Atlantic salmon, terrestrial invertebrates were of greater importance for diets of 1+ and 2+ year brown trout. Terrestrial prey biomass was generally greater than aquatic prey for 1+ and 2+ year brown trout across seasons and riparian types. Total prey numbers captured tended to be greater for all age classes in streams with a deciduous riparian canopy. In Finland, Syrjänen *et al.* (2011) assessed the importance of terrestrial and aquatic invertebrates to salmonid diets in 25 streams. Across all 25 streams in autumn, blackfly and caddis larvae were the most important prey items. Terrestrial invertebrates were of moderate importance in all streams, including the smallest. The proportion of terrestrial prey was highest in streams flowing through deciduous forests.

Egglishaw (1967) found that Dipteran, Hemipteran and Hymenopteran species made up 50% of the diet of brown trout in one Scottish stream and 80% in another.

Published research for woody riparian buffers showed that riparian vegetation played a key role in the composition of the Salmonids diet, even more so than seasonal effects on the Tarland Burn (Van de Weyer, 2014). Although the sample sizes were small (3 sites x 100 m reach sampled, repeated spring and autumn), the data suggests a link between tree cover and the proportion of terrestrial

[39] New maps (spatial) are available to help managers prioritise the location of bank side tree planting. These mapping tools can be accessed through the National Marine Plan Interactive (NMPi) website, or brought into a local Geographical Information System (GIS) using Web Based Mapping (WMS) services, where it can be layered over other maps showing other priorities (e.g. sources of diffuse pollution) or constraints (e.g. landowner approval) on tree planting.

invertebrates in the diet. The high deciduous tree cover (35 trees along a 100m reach and within five metres of the stream) site (Site 13) had a higher proportion of terrestrial invertebrates in fish guts in both spring (57.24%) and autumn (44.74%) compared to the low tree cover site (Site 14) of 9.4% (in spring) and 3.4% (in autumn).

However, Bridcut (2000) did not find a difference in the proportion of terrestrial and aerial organisms in the drift or in salmonid guts between moorland and forest sites within the River Nethy catchment in Scotland over a 12-month period. A study in New Zealand has shown that the mean biomass of terrestrial invertebrates that entered streams in tussock grassland and forest areas was significantly higher than biomass that entered streams in more intensively managed pasture (Edwards & Huryn, 1996). This paper and the Tarland catchment study indicate the important influence of land-use type on the availability of terrestrial invertebrates to stream fishes. Further field work in Scotland, with gut analysis on more streams and across Scotland, will be beneficial to test and potentially strengthen the evidence that semi-natural riparian woodlands compared to more intensively managed land-use types will improve invertebrate abundance and food sources for salmonids.

Factors influencing effectiveness
The importance of riparian tree cover for the provision of terrestrial insects for fish diets was indicated by a study on the Tarland Burn in Aberdeenshire (Van de Weyer, 2014). The density of riparian trees was also a factor in this, with high tree cover providing a higher proportion of terrestrial invertebrates in fish guts in both spring and autumn compared to the low tree cover site. There is likely to be a greater difference in the provision of terrestrial insects between riparian woodland and high intensity agricultural land, than between riparian woods and other semi-natural habitat types in the riparian zone (as per (Edwards & Huryn (1996) and Bridcut (2000)). It is possible, although as yet unresearched, that factors such as the maturity of riparian trees, species diversity of trees and woodland management regimes might also influence the composition and abundance of terrestrial invertebrates available to fish from river woodlands.

3.9.4 Improving habitat for fish with large woody material

Functional processes
Large woody material has important functions in relation to fish populations as it is a source of invertebrate food, provides cover and protection from predators, protection from currents and adds to the diversity by increasing the number of territories (McKenzie, 1996). Large woody material, which includes fallen trees and branch litter, divert and obstruct flows which can create a more complex diversity of flow-types and forms pools which provide slow water refugia for fish, and gravel deposits, which are important fish spawning and rearing areas (see section 3.7.6 for further detail). These varied habitats may also be beneficial for other components of the fish community. Deposition of fines, such as silt and sand may provide suitable habitat for juvenile lamprey (brook, river and sea), and the gravels may provide suitable spawning habitats for adults of these species (Maitland & Campbell, 1992). Sub-surface objects such as large woody material and tree roots permit an increase in fish numbers by allowing territories to exist in close proximity (McKenzie, 1996). The habitat requirements of brown trout, Atlantic salmon have been extensively studied (see review by Armstrong *et al.*, 2003), as well as those of other native freshwater fish and other aquatic species. But it is clear that further work is still required to fully understand how modifying habitat during restoration (such as involving large woody material) influences their interactions and subsequent impact on fish distributions and abundances (Armstrong *et al.*, 2003).

Measured effect
On the Aberarder Estate, on the Upper Nairn, strategically placed large woody material has allowed the channel to rapidly adjust to a 'dynamic pool riffle morphology' characterised by alluvial bars, riffles

and pools. Site monitoring has shown an increase in the number of Atlantic salmon redds (providing an indication of the amount of spawning taking place) compared to pre-restoration figures. Monitoring included repeat spawning surveys /redd counts (including pre-works and two spawning seasons post-construction) and repeat electro-fishing surveys (in both channel and wetland locations, pre- and post-works) (Upper River Nairn Restoration Project, European River Restoration) On the River Gairn and River Muick, at the end of 2021, 137 large woody material structures had been strategically placed using locally sourced dead trees with the aim of improving habitat availability and diversity for Atlantic salmon. At the end of 2020, 12 of the 40 structures installed on the Muick, showed clear evidence of Atlantic salmon spawning adjacent to the new structures. On the River Gairn, alluvial bars have developed downstream of the large woody material, higher water depths are maintained through pool formation, there is good riffle parr habitat development and shallow fry habitat has been created along the bank edge behind the structures (Caithness *et al.*, 2020).

Cbec Eco Engineering applied a full restoration strategy for the Allt Lorgy Burn, a tributary of the River Dulnain in the River Spey Catchment in the Scottish Highlands with the aim of reinstating dynamic geomorphic and ecological processes. This involved the addition of large woody and gravel augmentation and the removal of flood embankments (Williams *et al.*, 2020). The development of gravel-bar features has been associated with increased spawning habitat that has already been utilized by sea trout and Atlantic salmon.

Many of these projects have not been in place long enough to understand fully the benefits and risks associated with the restoration of woody material to the channel and do require further long term monitoring. On the Rivers Gairn and Muick, to evaluate the benefits, further monitoring by PhD students is being carried out from the James Hutton Institute and the University of Aberdeen (water temperatures), the River Dee Trust (fish populations) and cbec eco engineering (hydromorphology).

There is empirical evidence in the international literature on the benefits of large woody material providing habitats for fish (in reviews by McKenzie, 1996 & Feld *et al.*, 2018). Dolloff & Warren (2003) reviewed the impact of large woody material in North American river systems and found that the life histories of more than 85 species of fish have been found to have some association with large wood for cover, spawning (egg attachment, nest materials), and feeding (Dolloff & Warren, 2003). This included a study in eastern England where trout (*Salmon trutta*) and minnows were found to be strongly associated with large wood (Punchard *et al.*, 2000). Sievers *et al.*, (2017) found in a global meta-analysis of studies predominately from North America and with control-impact designs, that there are positive effects for a range of trout species from the addition of large woody material with a response ratio close to 1 (where a ratio of 0 to 3 is positive and 0 to -3 is negative and 0 represents no significant effect). Studies of brown trout specifically, which is native to Scottish rivers, had a weakly positive response ratio just above zero. It has traditionally been assumed that habitat quality and quantity limits fish population growth and the restoration of habitats will increase both population size and individual growth rates. However, restoration could simply attract fish from elsewhere, leading to a redistribution of individuals rather than an increase in net population abundance. The research by Sievers *et al.*, (2017) provides some indication that, at least in the short-term, fish productivity is likely to be unaffected by woody debris addition and stock exclusion, and thus, the observed population enhancement may be a direct result of migration and movement. However, the responses (almost exclusively size and growth) assessed may be poor indicators of population productivity, and more work is needed, especially incorporating the collection of data on survival and reproduction, to examine if trout productivity can be enhanced by changes to riparian zones.

It is acknowledged that the benefits of large woody material can be species specific for fish (Feld *et al.*, 2018) which emphasizes the importance of further Scottish research projects in this area with a focus on native Scottish fish species. Such studies should involve long-term monitoring and projects should be set up with a well replicated BACI design so that impacts and progress can be effectively measured.

Factors influencing effectiveness

Forest type and age will influence the amount of wood in streams (McKenzie, 1996). Young growth will provide litter but results in streams with less cover and fewer pools for fish than older growth forests. In Scotland, large woody material is being placed in streams, as part of restoration, to kick start morphological and ecological processes in conjunction with planting trees. It is the intention that when the trees grow older, they will be able to provide the large woody material. The location and design of this large woody material in streams and rivers will influence the effectiveness of kick-starting these processes and engineering design models are available to help with appropriate placement in streams to maximise effectiveness of such measures.

The diversity of habitats within both the riparian zone and the stream channels is key to optimum fish and invertebrate populations because of the many different habitat requirements between different species and stages of the lifecycle (McKenzie, 1996). A stream reach which consists of riffles and runs may have adequate feeding and spawning areas, but not be able to hold mature fish during spawning time because of the absence of pools and cover. A diversity of biotic and abiotic habitats are essential if all stages in the life cycle of any given species are to be sustained (McKenzie, 1996).

There is abundant evidence that habitat requirements of Atlantic salmon and brown trout overlap and there is scope for interactions between them depending on the spatial arrangement of habitats and the occurrence of bottlenecks (Armstrong e*t al*., 2003). It is particularly important to understand where the bottlenecks to production lie and to focus on these in the first instance. Otherwise, there is a risk of manipulating habitat that is already in excess, or increasing numbers of a population that will subsequently be constrained, e.g., by over-wintering habitat. For this reason, it is prudent to accept that although manipulations of habitat may appear to be beneficial when considered locally, they should be measured and assessed where possible in terms of the production of returning adults and/or high quality smolts.

3.9.5 Evaluation of evidence

Strength of evidence (based on quality of studies)

Regulating local climate through shading: The thermal dynamics and heat exchange processes which underpin the function of riparian woodlands to moderate and cool stream temperatures are well established and understood. This is backed up by empirical field work and modelling parameterised by field data in Scotland. Results show that there is **strong** evidence of a buffer cooling effect on water temperature in summer which is related to the presence of trees. There are very few studies that quantify a net positive effect of riparian woodlands on fish populations compared to other land-use types in Scotland, so the evidence remains **weak**. However empirical evidence including modelling work from overseas, does indicate that under extreme summer temperatures, there is a positive effect for fish.

Providing food for fish: There is **moderate** empirical evidence from studies that terrestrial invertebrates from riparian woodlands trees can make up a substantial portion of the diet of salmonids from fish gut analysis with supporting evidence from Scotland. Other semi-natural habitats provide similar benefits in terms of provision of invertebrates for food for fish. More intensive agricultural land-use provides a poorer source. 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.

Improving habitat for fish with large woody material: There is **strong** evidence from the international literature (mainly North America) that shows that large woody material (including submerged tree roots) provides habitat for fish in general (for food, shelter, cover from predators). Currently in Scotland, there is a moderate evidence base, quantifying how large woody material allows channels to adjust rapidly to dynamic pool/riffle morphology and this evidence is growing with the ongoing collection of robust empirical topographical field data. Observations in the field, has shown that this can lead to an increase in spawning habitat for Atlantic Salmon and brown trout but there is no data to quantify the positive effects of additions of large woody material for Atlantic salmon or brown trout production, yet so the evidence remains **weak**.

Limitations and Gaps in Research

The salmonid egg stage is the most vulnerable life stage to any increase in temperature as a result of climate change. In winter when salmonid eggs hatch, very few will hatch at the upper limit of their thermal range, and the optimum range over which the highest percentage of eggs hatch is much lower at 4–7°C for Atlantic salmon and 1–8°C for Brown Trout (Elliot & Elliot, 2010). However, the effects of the woodland measures to moderate river temperatures are restricted to late spring and summer seasons.

Further research is required to understand cooling, warming and insulating effects under different riparian canopies with or without the influence of groundwater discharge.

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.

There are few studies which have sufficient data to identify whether river woodlands have an overall net benefit to fish populations in Scotland over other land-use types. Current research and monitoring analysis under the National Electrofishing Programme for Scotland (NEPS) seeks to relate Atlantic salmon productivity to water quality and presence of woodland[40].

Further work is required to assess variability in invertebrate productivity, drift and salmonid diets between landuse types to better ascertain whether semi-natural riparian woodlands are able to support greater abundances and biomass of salmonids than more intensively managed land-use types. In a related area, Further work is required to understand the complex interactions between food availability, competition (within and between fish species) and growth.

There is no scientific evidence in Scotland that large woody material will have a positive impact on the numbers or biomass of Atlantic salmon, brown trout or other species. Further research is required to understand the effects of large woody material on habitat and on the production of different native fish species. It will be important to understand how modifying habitat during restoration involving large woody material influences their interactions and subsequent impact on fish distributions and abundances.

Monitoring needs to be at a sufficient spatial scale to demonstrate net benefits at tributary (rather than reach) scale and should preferably be of a BACI design. Monitoring should also account for inter-annual variability and be long-term. In some cases where habitats are not saturated, experimental stocking could provide some information, in less sensitive sites but this should be tightly controlled.

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[40] More information on current research National Electrofishing Programme for Scotland - gov.scot (www.gov.scot

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. However, the development of such models will be helpful in understanding the ecological impact of changes in hydraulic habitat and habitat quality.

3.10 Sustain food production

3.10.1 Overview of benefit

River woodlands can provide multiple benefits to fruit, arable and livestock farms and this includes a valuable contribution to sustainable food production. Planting trees and shrubs in buffer strips and on the floodplain provides livestock with shelter and shade from adverse weather (e.g. sun, rain and wind) alleviating temperature stress further benefitting production and welfare. (Blyth *et al.*, 1987; Broom *et al.*, 2013). Traditionally tree fodder has been an important animal feed and has the potential to contribute to nutritional or health needs of the animals (Smith *et al.*, 2018) and reducing supplementary feed costs (Perks *et al.*, 2018). River woodlands can provide a valuable contribution to the diversity of habitats in the landscape which support the survival and lifecycles of essential insect pollinators, providing habitat and a range of food sources throughout the season. Honey bees, wild bees, flies, and a variety of other insects support insect-pollinated crops. Many crops (75% of crops worldwide) need insect pollination to assure the amount, quality, or stability of yield. In Scotland, the most important commercial crops benefitting from this are oilseed rape, strawberries, raspberries, black and red currants, apples and beans, all of which contribute to a vibrant economy[41]. In Scotland, the economic value of pollinators is in the order of £43 million per year for agricultural and horticultural crops, and honey (based on 2011 figures) (Aspinall 2011).

River woodlands can contribute to agroforestry, with agroforestry taking many forms that include shelterbelts, wide spaced trees, groups of trees, hedgerows and woodland grazing (Perks *et al.*, 2018). Riparian woodland buffers have been defined as a type of shelterbelt (Perks *et al.*, 2018) and can also contribute to important field boundary trees. Increased use of agroforestry in Scotland is one option that could help contribute to both climate change mitigation and adaptation. Agro-forestry can improve a farm's resilience to a changing climate by providing shelter to animals and crops, reducing feed costs, reducing risk of flooding, improved animal welfare, reducing soil erosion and moisture extremes and diversifying farm income. The need for shade and shelter for livestock and crops is becoming a higher risk (CCRA, 2017) with climate change with an increase in frequency of extreme weather events such as storms, drought and heat waves.

There is concern that key pollinators and other beneficial insects are declining. In Scotland, for example, there is evidence that the geographic ranges of four out of 12 bumble bee species have contracted (Powney *et al.,* 2015). This is part of a wider UK trend that is partly linked to declines in forage availability for bumblebees, with 76% of bee forage plants shown to have declined since 1930 (Carvell *et al.*, 2006) and pesticide use affecting wild bee behaviour (Stanley *et al.*, 2015). A UK pollinator occupancy indicator index across 377 wild bee and hoverfly species found that occupancy in 2017 had declined by 30% compared to its index value in 1980. Whilst 19% of species had become more widespread, 49% had declined. The decline mostly relates to hoverflies, with wild bee populations fluctuating and showing a 9% decline in the wild bee index over the same period[42]. It is this concern about the long-term loss in pollinators, and the implications of this for key food crops and maintaining landscapes in Scotland that prompted the development of the Pollinator Strategy for Scotland 2017-2027.

[41] Pollinator Strategy for Scotland 2017-2027 | NatureScot
[42] UKBI - D1c. Pollinating insects | JNCC - Adviser to Government on Nature Conservation

This section focuses on the three main functions of providing shade and shelter for improving livestock production, providing tree fodder for improving livestock production, and supporting the life cycle of insect pollinators for crop production. Agricultural production is also supported through benefits, discussed in other sections in the report. For example, there is evidence of how river woodlands contribute to sustaining soils through reducing soil loss and enhancing soil fertility which is explored in section 3.6 and reducing impact of water stress on crops in section 3.2.2.

Beneficiaries

Fruit (especially soft fruit) producers, arable and livestock farmers, land and estate managers, and food industries relying on crop production and good quality products including meat.

3.10.2 Providing shade & shelter for livestock

Functional processes

The biophysical processes which underpin the shade and cooling function provided by trees are well understood. The cooling effect of trees on ambient air temperature under the trees have also been quantified in the rural and urban environments with measurements in the field and with modelling work (see section 3.2.2 on drought adaptation & section 3.8.3 on health benefits). Shade from riparian trees can overlap both the water and field boundary with a cooling effect from the water extending out over the bank.

River woodlands provide effective shade for livestock such as sheep

The principles and biophysical processes which underpin woods and trees ability to provide shelter to animals (and crops) are well known and described within farm woodland management textbooks on shelterbelts, blocks and windbreaks (Blyth *et al.*, 1987), in British Forestry Commission technical publications (Gardiner *et al.*, 2006; Caborn *et al.*, (1957) and agroforestry and wood pasture literature. Understanding the biophysical processes are important for design purposes to maximise effectiveness of measures for shelter. Caborn's research on shelterbelts and microclimates is backed up by laboratory and field work in Scotland (Caborn *et al.*, 1957). Shelter woods affect microclimatic conditions by modifying airflows which affects wind speeds but also turbulence intensity, temperature, humidity and soil erosion and described by Gardiner *et al.*, (2006): Within the wood, wind speeds can be reduced (depending on design) reducing the exposure of animals to wind chill. For newborn lambs, the combined impact of wind speed and evaporation, of rain or amniotic fluid, mean the lamb rapidly loses heat through radiation and conduction. In the most extreme cases, where lambs are unable to generate sufficient heat, hypothermia is irreversible. Neonatal hypothermia is a significant cause of lamb mortality in many environments and outdoor shelter has a role in protecting lambs from wet and cold weather (Dwyer *et al.*, 2021; Pollard 2006).

Close to and within the shelter wood there maybe shading from the sun, which will reduce the temperature. This may be a disadvantage if solar heating or direct sunlight for photosynthesis and pasture growth is important (Gardiner *et al.*, 2006) but if overheating of animals is a consideration, it may be of benefit. Within the wake zone (area behind the shelter wood), the reduced wind speed and turbulence leads to a reduction in the movement of gases to and from the ground. This means that moisture levels are higher and there is reduced water loss from the soil. Close to the shelter wood, this may lead to waterlogging if the soil is particularly wet, or increased plant growth, if the soil is prone to drought. The reduced wind speeds can also lead to reduced soil erosion.

Woodland grazing by farmed ruminants for pasture and shelter has been taking place in Scotland for many hundreds of years (Smout, 2003; Smout, 2007). Ancient wood pastures are often linked to patches of natural woodland refugia such as gorge woodland (Quelch, 2001). Caborn (1957) identifies that the use of woodland pasture in Scotland provides two primary benefits to the farmer. First, it allows for out-wintering of hardy ruminant stock and therefore 'protects' the better-quality pasture or in-bye land, for the 'early bite' (first spring grazing) or for silage cropping; in upland areas the amount of land for fodder or lambing pasture is often a limiting factor. Second, it reduces maintenance requirements of livestock considerably, because the shelter reduces chilling. Wood pasture as part of an integrated silvo-pastoral system if managed well can encourage better pasture growth compared with an open hill grazing system in Scotland.

Much of the research which has been undertaken on the biophysical processes which underpin the functions of shade and shelter are based on general farm woodland and silvo-pastoral practice, but the general principles are transferable to river woodlands.

Measured effect

Extremes of heat and cold are a feature of the seasonal UK climate which can affect production. Shelter can increase lamb survival rates, by reducing the effect of wind chill and thus hypothermia, particularly in the early stages after birth, and can reduce feed requirements in the winter months as livestock exposed to cold conditions will require greater feed inputs in order to keep warm.

Controlled studies have been undertaken of the impact of shade (in general) for dairy cattle and beef cattle. In a global review of studies on beef cattle, including those in feed lots, shade has been shown to lessen the physiologic response of cattle to heat stress. Shaded cattle exhibit lower respiration rates, body temperatures, and panting scores compared with unshaded cattle in weather that increases the risk of heat stress. Results from studies investigating the provision of shade indicate that cattle seek shade in hot weather. The impact of shade on behavioural patterns is inconsistent in the current body of research, with some studies indicating that shade provision impacts behaviour and other studies reporting no difference between shaded and unshaded groups. There are many factors that impact heat stress susceptibility in beef cattle throughout the different supply chain sectors, many of which relate to the production system, that is, availability of shade, microclimate of environment, and nutrition management. (Edwards-Callaway *et al.*, 2020).

Research into the measured effects of the value of shade and shelter to livestock production is mostly from outside the UK, but does include temperate climates in Europe, New Zealand, South America and the USA. The research covers agroforestry without specific reference to river woodlands. A systematic review by Jordan *et al.*, (2020) into the value of shade and shelter for livestock production in temperate climates based on 289 relevant studies found only 14 that focussed on the impact on livestock production. The review includes grey literature case-studies as well as empirical peer-reviewed scientific literature. Of these studies, all bar one demonstrated that agroforestry had a positive effect on livestock survival, milk yield or heat and cold stress. However, this finding needs to be treated with caution because of the limited number of studies. The number of studies is also too small to confidently identify the factors (e.g., climatic conditions, tree species, tree planting density, etc.) that underpin the apparent variation in magnitude and direction of effects that is seen between studies. Most studies focus on the effect of agroforestry on pasture production, with 53% of studies finding that agroforestry adversely affected pasture production or production incrementally decreased with increased tree density (stems per ha), cover (% canopy) or proximity to pasture measured. However, only 20% of livestock growth studies found an outright negative effect. This disparity suggests that pasture production is not the only factor influencing livestock growth, and perhaps other factors including the effects of tree shade on reducing livestock heat and cold stress could be important. Observational results from the agro-pastoral field trials at the Glensaugh research station in Aberdeenshire, has found that if Hybrid larch trees are left unpruned or unthinned, the pasture is no longer productive but in mixed tree species plots where trees are slow growing, pasture production remains unaffected.

One study that focussed on the specific impact of tree shade on livestock production examined the effect of tree shade on dairy cattle energy metabolism, milk yield and milk composition in a temperate climate (Belgium). The controlled experiment included shade and no shade treatments on Holstein dairy cows over two summers, and one summer when the whole herd received the same treatment of no shade. Weather conditions were translated into a Heat Load Index (HLI) and body temperature of the cows (rectal temperature), and blood indicators of hyperventilation were measured. The cows were found to be significantly cooler with their body temperature rising less quickly under the shade conditions (0.02°C and 0.03°C increase per unit increase of HLI, for shade and no shade treatments respectively). Hyperventilation indicators increased for the no shade cows and did not occur for the shade group. Energy metabolism was also affected for the no shade group and unaffected for the shade group. After a lag time of two days the milk yield decreased with increasing HLI for the no shade cows whereas the shade animals milk yield was unaffected by HLI. The milk concentrations of lactose, protein and fat decreased as HLI increased, but only the effect on milk protein content was remediated by shade. In conclusion, access to shade tempered the negative effects of high HLI on cattle body temperature, hyperventilation and energy metabolism indicators (generally) as well as prevented the decrease in milk yield observed in cows without access to shade. (van Laer, *et al.*, 2015). Other studies of artificial shade found similar changes with respiration rates significantly higher when cows had less and no shade (Schütz, *et al.*, 2010). Therefore, it is not clear whether tree shade specifically is required, although the additional fodder benefit of the trees is not considered in either of these studies.

Research measuring the effect of shelter from trees and shrubs on-livestock production is limited with mixed results in terms of the benefits. A global review of shelter for sheep by Pollard (2006) found that, for Australian and New Zealand breeds of sheep, wind shelter (such as *Pinus radiata* tree shelter belts) generally removed less than 10% from lamb mortality rates, and in-field scattered shelter from tussocky grasses were more suited to sheep lambing strategies. In Scotland, Cresswell & Thomson (1964) undertook an initial study and found that within tussocks, wind speed reduced at lamb height (0.2m) by 40% of that at 1.2m. These authors considered that tussocky pastures afforded good shelter from wind and probably rain and snow, as well as providing fodder in snow conditions. However, they found that shelter did not affect the live weight gain of black face weather lambs between November and February. Results from the Glensaugh Agroforestry trials between 1988-2001, found that Greyface ewes benefited from the shelter provided by the trees in the silvopastoral plots and put on weight.

Modelling research in the UK, has been undertaken to understand windbreak effects on wind speed reduction and thermal benefits to sheep (He *et al.*, 2017). This included a field-scale simulation of a sheep grazing system, including wind-chill effects to estimate the net gain associated with including a windbreak in sheep productivity. The maximum productivity gain (27%) was found at a porosity of 0.5 and a wind speed of 12 m/s. Wind-chill effects were further simulated for lowland and upland environments and related to ovine-specific thermal tolerance limits. Results showed a distinct response to reduced wind speeds between sites, indicating different levels of thermal risk to livestock and different, microclimate-specific, windbreak benefits for each location.

In the UK and Scotland, quantified evidence on the measured effect of the benefits of shade and shelter to livestock is limited (and for river woodlands). However, there is much observational and anecdotal evidence from farmers that indicates that the value of trees and shelter for livestock is understood (Woodland Trust, 2017) (see Annex 2 for farmer's views) and practiced. Furthermore, the database from agroforestry trials is growing in Scotland.

The major agroforestry system currently practised in Scotland is silvo-pastoral, in the form of woodland grazing, shelterbelts and buffer strips (Perk *et al.*, 2018). The widespread occurrence of shelterbelts is testament to their value in mainstream livestock systems, particularly for the upland fringe including in Moray, Easter Ross, the Black Isle, the Borders and Fife in eastern Scotland (Perks *et al.*, 2018). Shelterbelts have also been established on crofts providing protection from strong prevailing winds such as on Lynbreck Croft in the Northern Cairngorms. The farm woodland on Lynbreck Croft provides invaluable shelter and shade to the Highland cattle and pigs and especially in hot summer drought conditions (such as in 2018).

Further data on the benefits of shelter and shade to livestock will be available as trees establish and mature at the Scotland's Rural University College (SRUC) Kirkton and Auchtertyre research farms in west Perthshire. This includes small-scale tree planting as shelterbelts on inbye ground to provide shelter for ewes and lambs and wood pasture and riparian planting blocks. Gorge woodland has also been established as part of a larger hill ground planting scheme (260 ha) to act as a wildlife corridor to link existing semi-natural woodland in the lower part of the gorge with main planting at higher altitude.

Factors influencing effectiveness

Design and management factors will influence the amount of shade and shelter provided to animals and crops. Design factors influencing the effectiveness of shelter woods includes height, porosity, width, length, orientation and are described well in Gardiner *et al.*, (2006): The design requirements will depend on the functional requirements. For example, dense (0-40% shelter woods create small and very sheltered zones appropriate for lambing, calving and feeding and protection of buildings. Tall semi-permeable (40-60% porosity) shelter woods provide effective shelter to the largest area and are most appropriate for sheltering arable crops and grazing animals.

The location of woodland blocks or narrow belts of trees in providing shelter is of considerable importance in determining their effectiveness for farm woodlands (Blyth *et al.*, 1987) and this would equally be relevant to riparian shelterbelt woodland and or woodland blocks within the riparian zone. Blocks tend to be more suitable for sheltering stock as animals can move into the lee of the block irrespective of wind direction. Shelterbelts provide a wider zone of reduced wind speeds when the wind is blowing at right-angles to their long axes and more suitable for sheltering immobile crops. As shelterbelts should be orientated at right-angles to the prevailing wind direction, the positioning of rivers for riparian woodland shelterbelts could be limiting depending on their location. Where rivers are deep-cut, river woodlands might not provide much shelter unless they extend onto the farmed ground above the river.

Successful implementation of a managed woodland in agricultural landscapes requires an understanding of the woodland management needs in addition to those of the livestock. A major constraint is the impact of deer on establishment and regeneration success. Another management issue to consider for riparian woodlands, is that livestock using them for shelter can result in compacted bare ground under the trees which can increase surface runoff, bank erosion and faecal indicator organism (FIO) contamination of the water (section 3.1.6). The exclusion of livestock from riparian woods has been found to reduce sediment from bank erosion in rivers (Hughes, 2016). The impact of poaching and erosion, however, will be influenced by stock densities, soil types, understorey vegetation, location (uplands, lowlands) and local climate (precipitation levels). Farm woodland advice is that poorly drained sites and frost hollows should be avoided to promote stability and to minimise poaching of land adjacent to the trees by concentrations of animals (Blyth *et al.*, 1987). Fencing is a major element of establishment costs and rectangular blocks will have lower fencing costs per unit area than long thin strips or belts.

Negative impacts of integrating trees into pasture in terms of reducing pasture productivity have been mentioned (Sharrow 1999; Devokta *et al.*, 2009). Shrubs and trees and pasture plants compete for above- and below-ground resources. Major effects on pasture production are shade, and the competition for moisture and nutrients, and these effects are tree and pasture species dependent (Sharrow 1999; Devokta *et al.*, 2009). Managing the appropriate species in the system is crucial; for example, in temperate systems, planting nitrogen-fixing trees such as Alnus spp. is expected to enhance nutrient cycling and increase soil fertility which may be beneficial to pasture plants (Smith and Gerrard 2015). Silvopastoral trials on the Glensaugh Research Station [43] in Aberdeenshire can benefit pasture production but this is influenced by factors such as the growth rate of trees, tree densities and sheep stocking densities. The management of the integrated sheep grazing and woodland system is key to maximising the benefits that shelter can provide for pasture growth, feeding and animal welfare.

3.10.3 Providing tree fodder for livestock

Functional processes

The high levels of minerals in tree fodder suggest that trees can offer an alternative source of supplement for UK ruminant livestock systems. The Organic Research Centre in Newbury, England have undertaken foliar analysis of the content of essential macro and micro minerals of tree species (Willow, Alder, Ash, and Elm) which include river woodland species. Leaves collected from a farm in Hamstead Marshall found that levels of phosphorus (an essential element for bones) were highest in dried goat willow (5.5 g/kg DM) (Smith *et al.*, 2018) but all trees compared favourably with grass at 2.8-3.5 g/kg DM, silage at 2.0-4.0 g/kg DM and at hay at 1.5-3.5 g/kg DM (McDonald *et al.*, 1995; in Smith *et al.*, 2018). With regards micro-elements, willow was particularly high in zinc with *Salix caprea* (goat willow) containing 144 mg/kg DM and *Salix viminalis* containing 245 mg/kg DM. The level of zinc in willow is substantially higher than those found in grass at 5 mg/kg DM, in silage at 25-30 mg/kg DM and in hay at 17-21 mg/kg DM (McDonald *et al.*, 1995; in Smith *et al.*, 2018).

Smith *et al.*, 2018 explain how Zinc is present in all animal tissue, organs and bones, playing an important role in growth, cell repair, hormones, enzyme activation, the immune system and skin integrity. The study also found that levels of iron were notably high in the dried samples and in elm, in particular, at 258 mg/kg DM. Furthermore, *Salix viminalis* and *Alnus glutinosa* contained substantially higher levels of manganese than did the other tree species.

Further foliar analysis research by the Organic Research Center has found that Willow (*Salix caprea*), oak (*Quercus spp*) and alder (*Alnus spp*) exceed the dietary metabolizable energy (ME) and crude protein (CP) concentration requirements for growing lambs (40 kg lamb @ 150 g/d) (Kendall *et al.*, 2021). Tree leaves were collected from three sites in the UK in June as well as September. Alder contained the most ME and CP of the studied species. Zinc and cobalt concentrations were found to be dependent on tree species with negligible site and season effects. All sheep nutrient requirements of both elements were exceeded by willow, met by alder and not met by oak, willow exceeded these requirements for zinc and cobalt by approximately 3-6 and 10-15-fold respectively. The zinc and especially cobalt concentrations of willow leaves were sufficient to suggest that willow could be used

[43] Glensaugh Research Station. Sharing best practice on agroforestry in Scotland

as a bio-supplement when fed within a conventional grazing system, especially useful for growing lambs.

Secondary compounds such as condensed tannins can also be of benefit by increasing the flow of rumen-bypass protein and essential amino acids to the small intestine (Rogosic *et al.*, 2017) (in Smith, 2018). The potential for self-medication in ruminants is not well studied in the scientific literature. Although salicin, in willow, is well known to have anti-inflammatory properties, it has not been widely evaluated in terms of its contents within tree fodder or consequent effects on animal health (Boeckler *et al.*, 2011) (in Smith, 2018). However, there is growing evidence that the condensed tannins found in willow fodder, has a protein-binding action that is anti-parasitic reducing livestock parasitism, reducing nematode fecundity (Mupeyo *et al.*, 2011) and leading to lower worm counts in livestock (Diaz Lira, 2005).

Measured effect

Research into willow (a common riparian woodland species) as a source of browse for sheep during drought in temperate regions has been widely investigated for its impacts on animal performance and reviewed by Vandermeulen (2017). It has been reported to improve reproductive rate, e.g. by 20% in ewes, with more births of twin lambs (Pitta *et al.*, 2005) or by 17 lambs/100 hoggets mated as a result of increased oestrus activity and conception rates (Musonda *et al.*, 2009), and reduce post-natal lamb mortality from 17.1 to 8.4 % compared to a control group (McWilliam *et al.*, 2005).

Studies have shown that ruminants dosed with condensed tannins, both in tree fodder and as an extract, can have a significantly reduced load of nematodes within a month (Woodland Trust, 2015). A rotational grazing experiment conducted for 14 weeks in New Zealand compared the efficacy of grazing willow fodder blocks containing condensed tannins for sustainable control of internal parasites in 180 Suffolk x Romney weaned lambs. One third of the lambs grazed control pasture, another third, pasture for three weeks followed by willow fodder for one week and the last third of the lambs grazed on willow fodder blocks all the time (full access). Results found that lambs in the willow fodder block (full access) had the highest liveweight gain in drenched as well as undrenched lambs of 180g/day and 154 g/day respectively (Diaz Lira, 2005).

Farm research trials on the nutritional and medicinal benefits of tree fodder are on-going in the UK and it will take time for quantifiable data to be available. The main aim of the farm trials on a dairy farm in Shropshire are to analyse the nutritional content of the tree fodder, record milk volume and quantify overall cow health with an overall objective that the animals will have access to more feed value, become less stressed and be more productive for longer (Woodland Trust, 2015). In Scotland, interest in the use of tree fodder is growing, and in particular, amongst crofters practicing silvopastural agroforestry such as on Lynbreck Croft in the Northern Cairngorms and Darach Croft in Ardnamurchan. Observations on Highland Cattle browsing preferences on tree hay harvested from existing pasture woodland have been made at Lynbreck Croft and tree fodder blocks established.

Factors influencing effectiveness

Palatability which is a measure of the attractiveness of a species being browsed probably relates to digestibility and toxicity. This will vary with tree species, the condition of the tree (affected by many factors including season, site and health) and the type, condition and individual tastes of the browsing animal. Large ruminants can generally extract more energy from low digestibility food than smaller ones.

Livestock browsing on tree fodder is influenced by the season and climatic conditions (Vandermeulen, 2017). In dry summer conditions, trees are browsed by animals when in the shade and as grass biomass declines. Research from Belgium found that dairy heifers selectivity fed on woody hedge species mostly when the available pasture biomass was lower. The use of willow as fodder in temperate areas of New Zealand is reported to secure forage supply during summer and autumn droughts (Vandermeulen, 2017).

3.10.4 Supporting pollination & other beneficial insects

Functional processes

The role of river woodlands in supporting food production relies on an understanding of how the woodlands contribute to maintaining a diversity of wild pollinator types, in sufficient numbers, throughout the flowering season of different crops, and how it supports them at stages in their life cycle when crops are not flowering. Different pollinators have variable rates of effectiveness in pollinating different crops. This is due to different fruits having different flower types that attract different types of pollinators. For example, about 8% of all flowering plants (including tomatoes and blueberries) have specialised flowers that release pollen through narrow openings at the tip of their anthers – a morphological adaptation analogous to a saltshaker (Free 1993), these are more suited to pollination by bumble bees, than honeybees with shorter tongues. The most common pollinator of field beans is the Buff- tailed bumblebee *Bombus terrestris*[44], which is common and found in large numbers, and suited to climbing inside the bean flower where the pollen is deposited on the heads.

Different pollinators are available at different times in the season, suiting crop varieties that flower at different times. Ellis *et al*., (2016) found that the relative abundance of different pollinator taxa visiting strawberries changed markedly through the season, demonstrating seasonal complementarity. Pollinators also vary seasonally and depending on the weather conditions, suggesting that pollinator diversity can reduce the risk of pollination service shortfalls. For example, flies visited the crop flowers in poor weather and at the end of the flowering season when other pollinators were scarce, and so may provide a unique functional contribution. Understanding how differences between pollinator groups can enhance pollination services to crops strengthens the case for multiple species management. (Ellis *et al*., 2016).

In a review of evidence based on observations, surveys and other research for a practical guide Falk (2017) identifies the key role of woodland edge habitats such as those created along river woodland edges provide valuable habitat for many pollinating insects (pollinators). Naturally occurring flowering plant species are most beneficial to pollinators as they provide sources of pollen and nectar throughout the season, whereas the agricultural plants they help pollinate may only have a particular season. The trees, deadwood and leaf litter also provide shelter and hibernating areas, supporting the life cycle of pollinators and other beneficial insects such as beetles and hoverflies which help manage pest species for crops such aphids (Falk, 2017).

Falk's evidence is supported by results from a Welsh national survey (July/August) and modelling of key factors affecting pollinator abundance. This found flower abundance in woodland edge habitats and the relatively undisturbed habitats in woodlands as key factors, especially for abundance of honeybees, hoverflies and mining bees. For example, high floral provision is found in broadleaved woodlands in Wales, particularly in the family Rosaceae. Ivy (*Hedera helix)* and brambles (*Rubus* spp.) were also identified as key food sources for adult stage pollinators. The role of woodlands in supporting other life stages of pollinators including undisturbed nesting habitats, and more stable microclimates were discussed as further factors influencing pollinator abundance associated with woodlands. However, bumble bee abundance was unaffected by habitat or ecosystem type. (Alison *et al*., 2022). This finding contrasts with other studies from more heavily forested landscapes in Estonia and Poland which found bumblebee species richness is negatively affected by forest at the largest spatial scales and is negatively affected by young forest such as willows at the edge of wetlands and

[44] Pollination | PGRO

along forest edges. These habitats are rich in blooming flowers in the spring (April and May), however species nesting here may struggle to find food resources later in the year, if there is not sufficient landscape diversity (Sepp 2004, Diaz-Forrera *et al.*, 2012, Bak-Badowska *et al.*, 2021).

Falk (2017) also identifies that some individual tree species are important for particular pollinators that also are important in pollinating fruits and arable crops. Several hoverflies and moths are associated with aspen, many other moths specifically require oaks, birches, willows, limes or elms, and several mining bee species only collect pollen from willows. Wet woodland and other wet features, including ponds, ditches, seepages and watercourses can be very valuable for pollinators. For example, shallow water, wet mud, wet mosses, and semi-submerged woody debris are used by some pollinating flies to breed in. In unshaded conditions, wet habitats tend to be in flower from early spring until early autumn, providing food for many pollinators. It is important that wet woodland is not drained. Limited tree-felling to create marshy clearings can be beneficial for pollinators, but as shaded wet woodland is also important, it is useful to maintain both open and shaded areas. The sheltered nature of woodland, and the presence of dead wood, old trees, leaf litter and dense vegetation makes it a valuable habitat for hibernating adult insects such as queen bumblebees, queen social wasps and certain butterflies and hoverflies.

The need for mixed open and shaded areas in the riparian zone is also highlighted in a review of the benefits of riparian buffers by Cole *et al.*, (2020). The review identified the importance of early flowering trees such as Salix spp. as important early season food resources for pollinators. However, some wooded buffer strips were also found to result in excessive shading, which decreases flowering plants at ground level, resulting in a lack of forage for insect pollinators when compared to vegetated buffer strips (Cole *et al.*,2017; Stockan *et al.*, 2012) which provide particularly profitable foraging habitats (Cole *et al.*, 2017,2015). Pollinators appeared to respond to changes in key floral resources, dynamically using different semi-natural habitats to meet their requirements. Maintaining landscape heterogeneity and improving the quality of semi-natural habitats to ensure resource diversity and continuity is fundamental to pollinator conservation. Riparian buffer areas and scrub provide key floral resources (Cole *et al.*, 2017). The need for landscape heterogeneity that includes trees was also supported by a Swiss study. Fabian *et al.*, (2013) found that insect communities in the wildflower strips strongly respond to the presence of forest habitats in the landscape (6.2-17% forest cover), with effects on species richness, abundance and food web complexity. The study concludes that in order to ensure long-term sustainability of wild bee and wasp communities and consequently their ecosystem services as pollinators and biological control agents, it is not only necessary to maintain and restore a dense network of flower-rich habitat patches in agricultural landscapes, but also to conserve a diverse landscape mosaic that includes forest areas.

For lowland temperate pasture systems, insect pollinators and flowering plants were investigated on a range of riparian margins (including fenced buffers with trees, and their adjacent grassland fields, to determine the main physical and botanical attributes driving pollinator diversity across 14 sites in Kirkudbrightshire and Ayrshire). Irrespective of whether they were fenced or not, riparian margins had richer plant assemblages and supported more pollinators than grassland fields (Cole *et al.*, 2015).

Pollinator benefits are most likely to be realised if native woodlands, rich in edges and managed gaps, are created on land which is currently flower-poor (Alison *et al.*, 2022). River woodlands and managed riparian buffers, provide extensive woodland edge with a range of moisture and soil conditions suiting a wide variety of flowering plants throughout the season. However, no studies were found that investigated the role of river woodlands specifically in supporting pollinator abundance and diversity, and the implications for crop productivity.

Measured effect

Evidence of the measured effect for crop production from improving pollinator populations is primarily from wildlife friendly farming measures in general with no evidence found on measured effects from wooded and river woodland areas specifically. However, diverse river woodlands including woodland edge, wet woodland and grassland habitats provide a range of habitats to support the life cycle of pollinators, as evidenced in the functional processes section above.

In a global review, Garibaldi *et al.*, (2013) found universally positive associations of fruit set with flower visitation by wild insects in 41 crop systems worldwide. In contrast, fruit set increased significantly with flower visitation by honeybees in only 14% of the systems surveyed. Overall, wild insects pollinated crops were more effective, an increase in wild insect visitation enhanced fruit set by twice as much as an equivalent increase in honeybee visitation. Visitation by wild insects and honeybees promoted fruit set independently, so pollination by managed honeybees supplemented, rather than substituted for, pollination by wild insects. Some solitary bee species, such as mason bees, are also better adapted than honeybees to pollinate apples, pears, plums, cherries, strawberries, raspberries and a wide range of garden flowers. The red mason bee, which is rapidly spreading naturally into Scotland (Robinson 2009), is widespread in England and has shown to be a promising pollinator for a number of crops grown in glasshouses or polytunnels; in particular for strawberry, raspberry and blackberry[45].

The need for a diversity of pollinators throughout the soft fruit season was found in a field study and through pollinator exclusion experiments conducted on two soft-fruit crops in a system with both wild and managed pollinators in Scotland (Ellis *et al.*, 2016). The study tested whether fruit quality and quantity are limited by pollination, and whether different pollinating insects respond differently to varying weather conditions. Both strawberries and raspberries produced fewer marketable fruits when insects were excluded, demonstrating dependence on insect pollinators. Raspberries had a short flowering season which coincided with peak abundance of bees and attracted many bees per flower. In contrast, strawberries had a much longer flowering season and appeared to be much less attractive to pollinators, so ensuring adequate pollination is likely to be more challenging. The proportion of high-quality strawberries was positively related to pollinator abundance, suggesting that yield was limited by inadequate pollination on some farms (Ellis *et al.,* 2016). These findings were similar in a study using controlled treatment by MacInnis and Forrest (2019) which found strawberries that developed from flowers visited by wild bees were heavier than flowers visited by honeybees. In addition, flowers visited by a combination of wild and honeybees produced strawberries that weighed less than flowers receiving purely wild bee visits in Quebec, Canada. It is noted that different wild bee species were present in the study to those found in Scotland. Similarly, apple tree fruit set significantly increased with species richness of wild bees over three growing seasons in Wisconsin USA, whereas managed fruit set by honeybees was not significantly different from those with and without managed honeybees (Mallinger and Gratton 2014).

There is scientific evidence that wildlife-friendly farming from relatively small plots across the landscape (equivalent to 1% and 5% of land in the whole landscape) increases field crop yield due to the higher abundance and diversity of crop pollinators (Pywell *et al.*, 2015). This single farm study in Central England found that habitat creation through sowing wild flowers in 50 and 60 ha patches on a commercial arable farm, lead to increased yields and the positive effect became more pronounced over six years. By enhancing habitat heterogeneity and ecological connectivity, riparian buffer strips have the potential to promote insect pollinators in intensively managed landscapes.

[45] A2360104-Pollinator-strategy-technical-annex.pdf (nature.scot)

The benefit in yield from pollinators varies by crop type and variety. There was an increase in yield for the field bean crop which comprised a mixture of self-fertile and inbred plants that must be cross pollinated to set seed. Pollination has been shown to be a key limiting factor for commercial beans (Pywell *et al.*, 2015). Insect pollination has previously also been shown to be a key factor limiting the yield of field beans in other studies on large commercial fields (Kendall and Smith, 1975). However, there were no detectable benefits or disbenefits were detected for crops of wind pollinated winter wheat, or oil seed rape which were self- pollinating or fully fertile varieties. (Pywell *et al.*, 2015). Other research using bagging studies have shown that insect pollination can boost yield and crop quality of oil seed rape (Bommarco *et al.*, 2012). Research published by the Processors and Growers Association advises that pollination reliance varies by variety. For example, bumblebee pollination increases yield of Wizard beans by around 15% under normal conditions compared to plants receiving no pollination. Quantified yield benefits in other varieties range from 17 to 30% and can rise to over 50% when crops are affected by heat stress. Yields of bee-pollinated plants can also be 20% less variable, and plants can have greater harvest index, shorter straw, and earlier ripening. It is unclear whether insect pollination changes seed size, and there is no evidence that it affects protein content[46].

Factors influencing effectiveness

Good design and management of riparian woodland buffer strips are important to maximise pollination benefits. Excessive shading decreases flowering plants at ground level, resulting in a lack of forage for insect pollinators when compared to open vegetated buffer strips.

While the erection of fences did not enhance the richness or diversity of flowers, fenced riparian buffer strips supported more even and diverse assemblages of bumblebees and a greater number of butterflies than unfenced riparian margins. More bumblebees and butterflies were recorded in wide buffer strips (i.e. over five metres wide) than in unfenced margins or narrow buffer strips (i.e. ≤3.5 m wide) and butterfly assemblages in wide buffer strips were richer and more diverse. (Cole *et al.*, 2015).

In Cole *et al.*, (2015), the majority of plant-pollinator interactions (87 %) occurred on just seven plant species, indicating their value as resources for insect pollinators (i.e. *Symphytum×uplandicum*, *S. sylvatica, S. palustris*, *Trifolium repens*, *Cirsium palustre*, *C. arvense* and *C. nigra*). The abundance of these key flower species, rather than the total abundance of flowers, is likely to be a more important determinant of insect pollinator populations in the study area. With the exception of *C. arvense* and *T. repens*, flowers of these species were more abundant in fenced buffer strips than unfenced riparian margins. Furthermore, pollinators in narrow buffers strips were never recorded foraging on plant species identified as providing key resources early in the season (i.e. *Symphytum×uplandicum*, *S. sylvatica* and *T. repens*), indicating the importance of wide buffer strips, and indeed unfenced riparian margins, in providing resources early in the season (Cole *et al.*, 2015).

While mowing is a realistic option to maintain botanical diversity in arable landscapes where buffer strips can be established without fencing, in grassland situations, grazing is a more viable management option, due to the difficulties in manoeuvring machinery in the confinements of fenced field margins. Grazing disturbance can increase the longevity of botanical diversity within field margins, thus benefitting insect pollinators (Carvell, 2002; Fritch *et al.*, 2011). Allowing livestock access to riparian buffer strips, however, increases the risk of faecal contaminants entering the watercourse and thus grazing management should be implemented outside of the bathing season to minimise risk to human health (McCracken *et al.* 2012- From Cole 2015).

It took around four years for the beneficial effects on crop yield to manifest themselves and these appeared to strengthen with time. This could be considered further indirect evidence of biodiversity-

[46] Pollination | PGRO

mediated benefits to crop production, reflecting the time taken for populations of pollinators and other beneficial insects to respond to wildlife-friendly farming. Recent studies show increases in the numbers of pollinating insects over similar time periods in response to creation of pollen and nectar habitats across a landscape gradient (Pywell *et al.*, 2015).

3.10.5 Evaluation of evidence

Strength of evidence (based on quality of studies)

Providing shade for livestock: There is **strong** evidence of the biophysical processes that provide a shade provision to livestock via cooling effects of the trees. There is **strong** empirical evidence from controlled physiological studies which demonstrate the positive impact of shade on dairy and livestock production. It is not, however, specific to river woodlands and there is concern that encouraging use of river woodlands by animals may have adverse impacts on water quality.

Providing fodder for livestock: There is **strong** evidence which has quantified the nutritional properties of tree leaves (including riparian woodland tree species). The quantified benefits of fodder for livestock welfare and productivity (including quantifying positive medicinal impact) however remains **moderate** overall and research trials to quantify the benefits are on-going in the UK. The evidence is stronger for sheep browsing willow with benefits of improved reproductive success and reduced loads of parasitic worms with improvements in growth. No work has been undertaken in the UK for river woodland types although the benefits of browsing woodland edge or hedgerow trees with similar tree species (eg: willow) adjacent to fields are likely to be transferable.

Providing shelter for livestock: There is **strong** evidence for the biophysical processes which underpin the ability for shelterbelts and wood pasture to provide shelter to livestock. Quantified evidence of the measured effect of the benefit of shelter to livestock and dairy production from woodlands is limited but it is **strong** for sheep and lambing (with multiple lines of moderate observational evidence). It is likely that the benefits from shelter from shelterbelts and woodland pasture is transferable to riparian woodland although there are limitations with potential conflicts with animal welfare, soil and water conservation close to water. Shelterbelt riparian woodlands buffers will be limited by the orientation of the river to the wind.

Supporting pollination & other beneficial insects:
There is **strong** evidence from multiple lines of observational evidence and robust surveys that woodland edge habitats and wet woodland habitats (such as created along river edges) provide valuable habitats and a range of food sources for many pollinating insects. The evidence is at field and landscape and national scales using statistical associations and modelling. The research indicates the importance of woodlands as part of a heterogenous landscape including other semi-natural habitats that provide a range of food sources throughout the season. There is **strong** empirical evidence that improving wild insect pollinator populations is beneficial for crop production from wildlife friendly measures in general but not wooded or river woodland areas specifically. However diverse river woodland habitats supporting the lifecycle of pollinators are likely to make a valuable contribution.

Limitations & Gaps in Research

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 if livestock use results in bare compacted ground under the trees. Furthermore there is a potential animal welfare risk if the riverbanks are steep and below deep water. Grazing livestock can also have a big impact on woodland ground flora which has previously not been disturbed. There is a Good Agricultural and Environmental Conditions (GAEC) requirement for farmers to limit the erosion of the banks of watercourses, water points and feeding areas from overgrazing or heavy poaching by livestock. 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.

The impact of the nutritional and medicinal benefits of tree fodder for livestock productivity requires further quantification in Scotland.

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.

3.11 Clean Energy - biomass production

3.11.1 Overview of benefit

Bioenergy can play a part in helping the Scottish Government achieve its renewable energy targets to help reduce greenhouse gas emissions. Advice from Scottish Government's statutory advisers, the Climate Change Committee (CCC), states that "sustainable bioenergy is essential for reaching net zero". According to the Scottish Government (2021), biomass provides two main routes to mitigate climate change and reduce emissions. First, as a carbon sink, it helps by removing carbon dioxide from the atmosphere and storing it for long periods of time in soils, trees and other plants. Second, as a renewable energy source, it helps by directly displacing oil, coal and natural gas use or by decarbonising the fuel source for the production of materials such as steel and cement. Bioenergy's overall contribution to Scotland's renewable energy target, is modest, 3% of final consumption from bioenergy and wastes. There is potential to expand production in Scotland, but there is concern about competing land uses.[47] The multiple benefits provided by river woodlands could be part of the solution to address these concerns. Willow or aspen planted as a riparian buffer has been suggested as a solution to help mitigate climate change as well as agricultural diffuse pollution, by sequestering carbon (see section 3.4) and by providing biomass through coppicing.

There are different opportunities for biomass production depending on the size and type of riparian woodland, from the provision of wood fuel, a farm scale bioenergy boiler to more intensive short rotation coppice schemes which can be sold as wood fuel or bioenergy crops for off-site biomass boilers serving businesses and the community.

This section reviews the evidence relating to provision of biomass from river woodlands and specifically from made-made riparian woodland buffers.

Beneficiaries: land managers, farmers, estate owners, utility companies, local authorities, rural communities and businesses using biomass fuel.

3.11.2 Provision of biomass for energy

Functional processes

A variety of crops can provide biomass for energy, however in the context of river woodlands the most likely species would be short rotation coppice (SRC) willow or poplar, as it would be combined in the design of woody riparian buffers for managing diffuse pollution. A review of the benefits from riparian buffers by Cole *et al.*, (2020) identifies there is a benefit of coppicing the trees to maintain the effectiveness of uptake of nutrients by the trees. Therefore, there is a co-benefit to harvest wood for

[47] Bioenergy: update - March 2021 - gov.scot (www.gov.scot)

biomass/timber with replanting or coppicing to maintain growth, nutrient uptake and the buffer strips ability to mitigate diffuse pollution.

SRC willow as an energy crop exploits the vigorous juvenile growth associated with Salix spp. and its ability to coppice, or re-sprout, from the stool that remains after harvesting. The crop does not need to be replanted after cut back. An SRC willow plantation is established from hard-wood cuttings prepared from one-year old stems. Growth is rapid after cut back and can be as much as four metres in the first year increasing to 6-8 metres at harvest in year three (short rotation) following cut back. The willow can be coppiced six to eight times giving the plantation a life span of 19 – 25 years, allowing for the establishment year. Shorter (2 years) and longer (four or five years) harvest cycles have been considered depending on the productivity of the sites and other end use factors (Caslin *et al.*, 2015).

A review by Christen and Dalgaard (2013), found that SRC could prolong nutrient uptake from wooded buffers and provide an economic incentive for landowners to establish wider buffer strips. They found a variety of buffer designs useable in different farm settings. They demonstrated the workability of one design at a trial site on a Danish farm and found that biomass buffers can deliver economic, conservation and farm management benefits.

There is also evidence that regular coppicing/harvesting of SRC, disturbs groundcover and exposes bare ground temporarily resulting in an increase in pollutants entering the watercourse. Therefore, design of the buffer and intensity of forestry management are key factors to consider. In order to make SRC both financially and environmentally viable it is suggested that SRC should be incorporated within a zonal buffer framework that combines a zone of coppiced trees with an undisturbed woodland zone immediately adjacent to the watercourse to intercept pollutants during harvest (Correll, 2005).

Zoning enables multiple benefits from a riparian buffer, with biomass and timber harvesting recommended in the middle zone away from the riverbank. Sheridan *et al.*, (1999) recommend zoning of the riparian buffer woodland so that there is a narrow zone of permanent native trees and shrubs immediately adjacent to the river (approx. 10m wide). This provides the benefit of stabilising banks and shading, as well as maintaining the river ecosystem. Then a second zone (45-55 m wide) behind this that provides the nutrient removal benefits through the woody material and infiltration and a grass buffer zone to capture sediments (8m wide). In field trials in the USA, management of zone 2 by selective felling and clear felling of the trees had little impact on the runoff and sediment load reduction function of the buffer, provided good forestry practices were followed such as not leaving areas of bare soil. This enables the landowner to gain an economic return from the woodland in zone 2.

There is also some 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 England (in Nesbit *et al.*, 2011). Further research trials are required in Scotland, but some work has started in Orkney. This suggests a wider planning for woodland biomass within the farmed landscape, with river woodlands providing a contribution to make it viable.

Alternatively, where water quality benefits are not the driver other species such as aspen could form part of a lower intensity wood pasture of pollarded trees providing forage and shade benefits (see sections 3.9 and 3.10), alongside biomass benefits. Aspen naturally grows on well drained soils near rivers. Trials in Germany have indicated that where a crop of aspen is harvested (cut at ground level) after ten years, as much as 45 stems/tree on average can regenerate. This will reduce naturally in more dense plantings through competition to two dominant stems from the stump and three suckers.

Based on the findings of Short Rotation Forestry (SRF) trials by Forest Research, the anticipated total biomass produced from such an aspen agroforestry scheme would be in the order 1T to 1.7T /Ha/yr depending on clonal variation. Biomass volume would be similar to that produced in an equivalent system utilising ash and would be more productive than a system utilising birch. While all the biomass available will not be utilised with pollarding, it gives some idea of the productivity of aspen (Eadha Enterprises, 2015).

Measured effect

Most of the studies reviewed, focus on biomass production from buffer zones where trees have been planted primarily for uptake of nutrients from farmland. There are controlled field-based trials in UK that investigate yield and carbon emissions that indicate the potential for biomass production from Short Rotation Coppice (SRC) from riparian buffers. One Italian study consider firewood production from a riparian forest buffer, which was not commercially viable.

Commercial levels of yields were found in field trials of Short Rotation Coppice (SRC) from riparian buffer strips. For example field scale trials from riparian willow buffers with an average plot size of 125m^2 in Northern Ireland had an average yield across all plots of 11.31 Mg dry matter (DM)/ ha/yr, assuming 10% harvest losses from mechanical harvest. The high yields are within the bounds of equivalent conventional SRC systems that required additional fertilizer inputs. High yielding willow varieties, good light conditions due to the narrow strip and fertilizer runoff from adjacent land explain the good yields achieved (Livingstone *et al.*, 2022). Similar commercial levels of yields were found in a study of Integrated Buffer Zone at Balruddery in Scotland. The biomass was removed from 300m^2 riparian buffer plots with 0.7% field ratio. The wood biomass produced from an integrated buffer zone with willow after two years was 17-40 DM tha^{-1}. The yields were considerably better for willow plots than for alder 2-10 DM tha^{-1}. (Zak *et al.*, 2019).

Life cycle analysis of using riparian buffers for biomass compared with conventional SRC demonstrates that they have lower carbon emissions due to no additional applications of fertilizer. The buffer plots were adjacent to an agricultural field and provided a 10m wide buffer zone to an agricultural drain, and runoff from the agricultural field was the only additional source of nutrients. Due to the proximity of the water course no pesticides were used. Emissions from the Northern Ireland plots were 4.66 kg CO2eq $GJ_{heatout}^{-1}$ which is equivalent to previous values for willow combustion. These were lower than 5. 84kg CO2eq $GJ_{heatout}^{-1}$ reported for the Irish system in equivalent climatic condition by Murphy *et al.*, (2014). This was largely due to the reduced fertilizer emissions. Compared with oil-fired heating the base case scenario had 95% less CO2eq emissions (84 CO2eq $GJ_{heatout}^{-}$). Even with an assumption of 250 km transport, CO2eq emissions were reduced by 91% compared with oil fire heating. These values are well within the RED II policy requirements for renewable energy from biomass sources. Overall, energy production is up to 64 times greater than the energy demands for the entire life cycle. (Livingstone *et al.*, 2022).

Narrow riparian buffers whilst still productive are less likely to provide commercial rates of return. For example, Dal Ferro *et al.*, (2019) studied a system where trees were grown for firewood in 3 and 6m buffers adjacent to arable land in an area of traditional farming practice in Italy. There was a motivation to also achieve multiple benefits for wood fuel production, as well as reducing suspended sediment, nutrient runoff, and pesticide spray drift. Designs of alternating Viburnum shrubs between plane trees were used with grass understory in three designs: a 3-m buffer single row, and 6-m wide single and double rows of trees. Coppicing was done every six to seven years by hand with chainsaws. The authors reported 33 to 52% greater wood yields attained in two-row than one-row systems, but 20% greater yield for trees closer to the field (1.5 m) than further away (4.5 m), indicating nutrient benefits associated with preferential nutrient trapping at the upslope buffer edge. Returns of 0.2 to 0.7 t dry matter per linear meter of buffer were insufficient to provide appreciable profit to farmers considering lost revenue of field crop and subsidies. The costs of management and firewood processing were only covered for sale when at the best well-seasoned quality price, even when factoring in EU environmental stewardship payments received for such buffers. Simple wood drying treatments were studied that increased profitability.

Factors influencing effectiveness

Appropriate design and management are required to maximise effectiveness and economic viability of short rotation coppice practice but also to minimise environmental risks to soils and water and for legislative compliance (see Annex 2). The design of the buffer for short rotation coppice will help with this as well as reduce nutrient pollution from adjacent agriculture (as described above).

The water use of short rotation coppice can be higher compared to agricultural crops which presents a potential water resource risk but reported vegetative evapotranspiration of short rotation coppice varies markedly depending on the location (precipitation, soil type), selected species/clones, plant age and the climatic conditions during the estimation periods (Dimitriou *et al.*, 2009).

Modelling exercises conducted by Stephens *et al.* (2001) indicated reductions of 10 to 15 % of the hydrologically effective rainfall in SRC fields compared to arable crops in the UK. Despite this, the authors claimed that the effect on hydrology to the catchment level would be minimal, after extrapolations based on the model results obtained and the assumption that 2500 ha SRC will be planted in an area of 40 km radius from a biomass-driven power plant.

Hall (2003) suggested that even if SRC "consumes" more water than other arable crops, catchment scale effects of SRC on hydrology will be negligible, and that even when used as riparian buffers SRC will have little effect on river or streams due to low abstraction rates. Hall (2003) suggested however that in places where the potential biomass production from SRC exceeds 12 t DM/ha/ yr, and precipitation happens to be lower than 550 mm per year, then these areas should be avoided for SRC planting since the consequences of reductions the hydrologically effective rainfall are much more serious in such areas.

Cole *et al.*, (2020) advise that the timing and intensity of harvesting of biomass should consider the full range of ecosystem services provided by the buffer strip and the relative importance of these at farm and catchment level. Furthermore, the extent of area in forest management, width of buffer including the permanent woodland zone that is not harvested impact on economic and environmental viability (Cole *et al.* 2020).

Harvesting techniques affect the overall lifecycle analysis. Use of grid electricity for mechanically drying chips also contributed to the acidification potential. In trials the biobaler method was found to outperform chipping and whole stem harvesting, and removed the need for mechanical drying, along with reduced transportation after field drying to 12% moisture content based on Canadian conditions (Livingstone *et al.*, 2022)

3.11.3 Evaluation of evidence

Strength of evidence (based on quality of study)

Provision of biomass: there is **strong** functional and quantified evidence from controlled field-based trials of commercial levels of biomass production from SRC willow from man-made riparian buffer strips, including Scottish evidence. Life cycle analysis demonstrates that biomass from riparian buffers has much lower carbon emissions compared with oil-fired heating (91-95% lower) and has lower emissions than conventional short rotation coppice. One Danish farm has demonstrated effective operation at a farm scale of economic, conservation and farm management benefits. A study of wide zoned buffers in the USA found that the wood could be harvested without impact on water quality.

Limitations and Gaps in Research

Ferrarini *et al.* (2017), identifies potential limitations of space when trying to use the riparian zone for biomass production as access with harvest machinery may be difficult unlike large scale bioenergy plantations. The type of machinery used to plant and harvest also impact on economic and environmental viability (Livingstone *et al.*, 2022).

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.

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.

4 Conclusions and recommendations

4.1 Strength of evidence for river woodland functions based on the quality of studies

A summary of the strength of evidence for river woodland functions is presented in Table 1. The strength of evidence is based on the quality of studies for each of the functions, with functions grouped into the benefits that river woodlands can deliver (column 1). The classification provides a level of confidence in the measures for investment purposes. The strength of the evidence ranges from very strong to weak. The majority of functions indicate a moderate to strong level of functionality based on empirical data quantifying a positive effect.

Table 1: Summary of the strength of evidence quantifying a positive effect for functions associated with each river woodland benefit. Classifications are based on the Level of Evidence Pyramid by Mupepele *et al.*, (2016) described in Burton *et al.*, (2018).

River woodland Benefit	Strength of evidence for functions of river woodlands			
	Very strong	**Strong**	**Moderate**	**Weak**
Clean water	Stabilising riverbanks	Controlling nitrogen pollution Controlling phosphorus pollution Controlling excessive algae & periphyton Capturing sediment pollution Capturing pesticides		Capturing pathogens
Conserve Biodiversity & Ecosystems	Supporting aquatic processes	Supporting other species 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 Reducing coarse sediment delivery and siltation of channels	
Climate action: Carbon			Carbon sequestration & carbon storage	
Clean air		Capturing air pollutants		
Sustaining soils		Reducing soil loss		Improving soil health
Good human health		Exposure to river woodlands 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 Providing shelter & shade for livestock	Providing fodder for livestock	
Clean energy Biomass		Provision of biomass for energy		

4.2 Recommendations

4.2.1 Over-arching themes

The following section includes the report's recommendations which are numbered under themes.

Design and location

River woodland measures need to be established with appropriate design and management to be effective and should be placed strategically within the catchment, in the right location(s) and at the right scale as this is critical for the delivery of the benefits.

1. River woodland measures need to be established with appropriate design following best practice guidance planting the right species in the right place.
2. The establishment of new native river woodlands needs to be integrated with deer management in Scotland.
3. New river woodlands should be placed strategically within the catchment with particular emphasis on headwater catchments for control of sediment, managing water temperatures, reducing flood risk by slowing flows, and supporting ecological functioning of the whole river.

Landscape scale approach

A landscape scale approach will improve delivery of many of the benefits and especially for clean water and flood alleviation. Sediment eroded from banks is often not a major source of polluting fine sediment, compared with sources direct from cultivated land.

4. Woodland should be strategically planted in the wider catchment on source-receptor pathways to stop erosion in the first place.
5. To optimise flood alleviation outcomes, river woodlands should be considered alongside wider catchment woodland and cross-slope woodland measures (Annex 3).

Component of sustainable integrated land management

Land-use management has an impact on the quality of soil, air and water. River woodlands help safeguard our environment, whilst providing climate change resilience and diversification on farms. They also provide an income and support agricultural production via carbon, pollination, biomass and agroforestry.

6. River woodlands should be considered as an important component of sustainable and integrated land-use management.
7. An integrated approach should be adopted for river woodland measures, considering multiple benefit delivery and other environmental factors (e.g.: water temperature) which may influence individual benefit outcomes.

Component of Scotland's Nature Networks

Establishing a network of riparian and floodplain woodlands enables nature to adapt to climate change by supporting reproduction and genetic diversity of species and species migrations. River woodlands will also contribute to biodiversity on a landscape scale as an important component of a heterogeneous landscape.

8. River woodlands should be established in agricultural, commercially forested and urban settings to increase structural diversity and the abundance and diversity of wildlife at the landscape scale.

Improve evidence

Improved evidence at catchment scale and over longer timescales will improve confidence in river woodlands as a nature-based solution. Estimations on the time it takes for benefits to be realised will be valuable for catchment planning, for example in identifying future needs of drinking water supplies or flood risk changes.

9. Direct evidence is required to build models for riparian woodland effects on benefit outcomes at catchment scales.
10. Longer duration studies are required to improve the evidence base as trees grow, and pre-intervention data on the sites of later intervention are needed to formulate more definitive Before-After-Control-Impact studies.
11. Data needs to be collected on the ecological and chemical status of freshwater in the headwaters of catchments (where most benefits will be delivered) as this remains a significant evidence gap and is required for the establishment of robust base-line data.
12. Approximate timescales to achieve different benefits and functions from river woodlands are required to produce more realistic objectives in line with nature-based solutions for River Basin Management Planning and other mid/long term scale initiatives.

4.2.2 Individual benefit /outcomes

Healthy & resilient river systems:
There is very strong evidence that native riparian woodland in the headwaters of catchments underpin the ecological functioning of the whole river.

13. Restoration of native riparian woodland in headwaters of catchments should be a priority for restoration.
14. A national map of existing and potential native riparian woodland cover needs to be developed for improved targeting of river woodland measures, that considers tree species for different regions and catchments and soil conditions.
15. Based on a national map of riparian woodland, tree nurseries for different tree species of riparian and floodplain woodlands should be set up to fulfil the need of future tree planting and river restoration projects.
16. The classification criteria of river morphological condition in SEPA should be improved, making use of the most up-to-date science on riparian woodland.

Clean water:
Man-made riparian woodland buffers are a viable and valuable measure within agricultural landscapes to combat the transfer of diffuse pollution to water courses. However, the effectiveness of buffers for diffuse pollution is highly variable depending on factors such as location, soils and land cover, size of buffer, design and management.

To maximise diffuse pollution mitigation benefits:

17. River woodlands should be at a correct scale of catchment coverage. This requires catchment coordination and planning to ensure targeting pollution sources and pathways, wider soil and land cover risks.
18. Headwater catchments require particular attention. Here, an understanding should be developed of dominant pollution sources and pathways, and woodland as part of pollution buffers should target multiple critical source areas to collectively improve water quality.
19. Planning, location and design need to consider local issues and knowledge.
20. Appropriate designs and siting of functional riparian woodland are particularly needed on farmland to mitigate pollution and protect water quality.

21. Management of man-made riparian woodland buffers is required to maintain effectiveness, which can include phased harvesting of biomass.

Climate action: adapting to water stress and drought:
Evidence suggests that planting of broadleaved woodland is likely to have a relatively minor impact on water yield and low flows, but further analysis of impact is required.

22. Hydro-morphological models need to be developed further to estimate woodland impacts on water resources to include river woodland types and species on sites across Scotland.

Climate action: alleviating flood risk:
Riparian woodlands, in combination with other measures such as leaky large woody structures and on-line ponds in the headwaters, have been found to slow up to medium-scale floods in small catchments in Scotland.

23. Natural flood management should consider river woodland measures to slow the flow and reduce sediment load; when used in combination with other natural flood management measures, these are most effective.

Climate action:
The carbon storage potential of river woodlands in Scotland could be substantial with contributions from whole tree biomass, large woody material and soil organic carbon within the river and wider riparian zone.

24. The different carbon components of river woodlands should be quantified and accounted for, for carbon sequestration estimates and the Woodland Carbon Code.

Clean air:
Roads often follow river courses and people are attracted to them for health and active travel, therefore targeting river woodlands in pollution hotspots would help reduce risks to people's health from ultra-fine particulates. However, riparian trees need to be planted with the right design and management to deliver improved air quality and avoid pollution swapping issues.

25. Urban planners should consider urban riparian woodlands to help capture air pollutants and reduce pollution loads.

Sustaining soils:
Healthy soils with good stable soil structure under river woodlands will be more resilient to pressures, including climate change impacts. Healthy soils provide a range of multiple benefits; protecting water quality, providing resilience to drought, reducing flood risk, improving carbon storage, conserving biodiversity and assisting in heat wave management in greenspaces to cool our towns and cities and reduce the risk of land loss and soils being washed away.

26. River woodlands should be considered as an important measure in safeguarding soils as a critical natural resource.

Conserve biodiversity & ecosystems:
Native riparian woodlands, floodplain woodlands and their associated large woody material support key hydrological, hydro-morphological and biological processes which are fundamental in maintaining resilient and healthy river systems. River woodlands also support a rich diversity of plant and animal species across the river and riparian zone, with strong, dependent inter-relationships.

27. The restoration of a national network of river woodlands in Scotland should be centre-stage in biodiversity conservation efforts to help avert our global biodiversity crisis.

Good human health:
Urban riparian woodland provides corridors to link up greenspaces for recreation and leisure and the cooling effect of the adjacent river and the woodland magnifies the benefit.

28. The design of urban blue-green infrastructure should consider river woodlands as they make a valuable contribution to improving health and well-being, including cooling our towns and cities.

Wild fish and angling:
It is clear that river temperatures in Scotland are increasing and that riparian woodland planting, along with managing river flows, are the main options available for climate change adaptation for cold water fish like Atlantic salmon and brown trout.

29. It is essential that riparian woodlands are restored to protect rivers from temperature extremes, now and for the future of cold-water wild fish and fisheries in Scotland.

Sustaining food production:
River woodlands enhance food production by providing shade shelter and fodder for livestock. They also can provide valuable habitats and a range of food sources for pollinating insects important for pollinating crops, especially fruit.

30. River woodlands should be considered as an option for the provision of shade, shelter and fodder for livestock, in fenced blocks on agricultural floodplains or behind fenced riparian buffers adjacent to fields.
31. River woodlands should be considered a key element within a heterogenous landscape alongside wildflower planting, hedgerows and other woodlands to support pollinating insects.
32. To optimise the benefit for pollination, river woodlands should be diverse, with a range of tree and shrub species, and designed to include open and wetland areas.

Clean Energy-biomass production:
Man-made riparian woodland buffers and zoned buffers provide commercial levels of biomass productivity with lower lifecycle carbon emissions than conventional biomass production.

33. Further farm trials to demonstrate the commercial benefit of biomass production from Short Rotation Coppice within man-made riparian buffer strips should be set up in Scotland. This should follow best practice on appropriate design and management to safeguard water and soil quality and avoid areas prone to flooding and water scarcity.

4.3 Recommended next steps for the Riverwoods initiative

1. Communications work is required to tailor the scientific evidence for specific audiences, including the buyers and suppliers of river woodland ecosystem services. Plans are in place to deliver some of this through the Riverwoods partnership.
2. A business case needs to be developed to enable effective delivery of river woodlands under the Riverwoods initiative (see Annex 2), underpinned by bespoke business plans for each Riverwood project. The business case should include:

- Assessment of the multiple benefits and quantifying financial returns and preventative spend from river woodland restoration.
- Specific information to understand individual and business views, interest and desire for investing in river woodlands in a given location.
- Further work to collate data on cost-benefit analysis relating to the restoration of river woodlands versus alternative measures for delivering the environmental and social benefits. This is being addressed through the Riverwoods Investment Readiness Pioneers project being funded by the Esmée Fairbairn Foundation.

3. Develop demonstration sites to show the pathway to investment ready projects and reduce uncertainty about outcomes for investors. These should be selected to include a wide geographical spread, range of river scales, different ownership arrangements, community and business interest, as well as representing both rural and urban locations. Early work on this has now begun.
4. Trees take years to achieve certain benefits such as shading, others like carbon storage are non-linear over time, with some benefits realised immediately; this must also be considered in investment and benefits calculations.
5. Further work is required to review the most up to date decision support tools and guidance for implementation to improve guidance for river woodland partnerships (see Design and Restoration Guidance links, Annex 2).
6. River woodland benefits should inform codes and standards supporting the development of natural capital markets and the shift towards a nature positive economy[48].
7. This evidence report has identified a number of research and development gaps for river woodland implementation which should be assessed for prioritisation depending on business requirements (see Annex 1).

[48] Scotland's National Strategy for Economic Transformation - gov.scot (www.gov.scot)

5 References

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Annex 1: Research and development

Research and development gaps highlighted in the Riverwoods technical science report are summarised below for each of the section chapters. The review found more research is needed on the role of river woodlands at a landscape and at catchment scales, in general.

Healthy and resilient river systems (Chapter 2)

- Maps of native riparian woodland and floodplain woodland structure and composition (including tree species) for different regions and catchments and land use objectives are required for national efforts for the restoration of healthy riparian corridors in Scotland.
- Biogeographical studies for riparian vegetation in Scotland are needed to inform assessment of ecological condition of riparian vegetation for Water Framework Directive purposes including reference condition work.
- Further work is needed to validate riparian vegetation indicators and establish their metrics and relative weights. New versions of MImAS in SEPA need to integrate most up-to-date scientific knowledge on riparian vegetation with morphological classification.
- The establishment of demonstration sites will be very important for investors to see how river woodland measures can be implemented on the ground. Morphological restoration and natural flood management opportunities involving river wood types have been identified in SEPA's Pilot Catchments which include the River Nith (Ayrshire), River Dee (Aberdeen-shire), River South Esk (Angus), Glazert Water (East Dunbartonshire) and River Leven (Fife). Examples include i/ the River Nith in New Cumnock where over two km of restoration works has been undertaken to set back embankments to provide space for riparian woodland; ii/ the Pow Burn (South Esk) where a two-stage channel has created space for large woody material and iii/ multiple initiatives on the Leven, to improve condition of the Back Burn, River Leven and Lyne Burn. Some of the original opportunities report are:

  -Nith FINAL REPORT (sepa.org.uk)

  -Dee-final-report.pdf (sepa.org.uk)

  -Restoration and flood management project River Sout Esk: Summary report (sepa.org.uk)

  -Working together to improve our water environment - Glazer Water (sepa.org.uk)

Assessment of benefits for people (Chapter 3)

Clean water

- The lack of data on ecological and chemical status of freshwaters in headwater streams is very limiting and a significant evidence gap.
- 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.
- Tools are needed to help with design of river woodlands at a landscape scale and to identify riparian buffer areas in a functional sense.
- More evidence is needed of the effects of (sub-) catchment-scale of riparian buffer management options to reduce nutrient and fine sediment pollution.
- Further quantitative evidence of the effectiveness of targeted woodland creation for reducing pesticide pollution is required in the UK. This includes quantifying pesticide load reductions in

waterways by riparian woodland buffers and understanding how woodland age and species structure influences effectiveness.

- Management and design of riparian woodland buffers is required to consider pathways for pollution swapping.
- Further development of modelling tools in Scotland to allow for the assessment of riparian woodlands on reducing coarse sediment delivery to watercourses. This includes root cohesion parameters in modelling tools.
- Further model development work is required to predict reductions of nutrients from river woodlands in waterways backed up with empirical evidence.
- Further empirical data in Scotland would be beneficial, investigating the role of riparian and floodplain woodlands in reducing soil erosion, retaining sediments and reducing sediment loading in watercourses. This includes potential roles in stabilising peat.
- Further work is required on the design and management of riparian woodlands to maximise benefits to control run-off and soil erosion and for different soil and slope combinations.
- There are shortcomings of evidence in terms of the limited studies that have controls in either space or time and especially with regard to absence of before intervention data for the definitive Before-After-Control Impact (BACI) study design.

Climate action: adapting to water stress & drought

- Better understanding of the role of natural floodplain woodland in maintaining river low flows in the UK.
- Further review work and field research on quantifying the benefits of different tree species on maintaining soil moisture content on different types of soils.
- Further research is required to understand if riparian and floodplain tree species can adapt to drought in Scotland.
- There is little understanding of how hydraulic lifting and bioirrigation processes would work in Europe, the UK and Scotland and thus no understanding of how to advise farmers on how to incorporate these processes into agroforestry designs in the UK. This is critical evidence to help feed into helping land managers weigh up changes in their land management practices.

Climate action: alleviating flood risk

- 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.
- Understanding how the type of riparian woodland, its placement in the catchment and the catchment's size affect its flood risk impact.
- 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.
- Better understanding of the impact of floodplain woodlands during larger flood events across a range of spatial scales and to improve flood modelling.
- Better understanding the effectiveness of leaky barriers and large woody material at mitigating flood peaks at larger catchment scales, and for larger flood events.
- Further developments in the design and construction of leaky barriers are required.
- Longer term monitoring is required to understand the impact of leaky barriers on reductions of sediment loads in waterways and flooding.

Climate action: carbon

- Further research and field data is required to understand carbon storage on different types of river systems in Scotland to include carbon stored in the trees, soils and large woody material.
- Further studies considering non-carbon Green House Gas emission impacts from changing land-use involving woodland creation.

Clean air

- Research is needed 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.
- Further study is needed 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.

Sustaining soils

- Further review work on quantifying the soil health benefits of river woodland is required in the UK and Scotland.
- 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.
- Further observation and modelling work to understand land and soil loss due to lack of stabilising trees in the riparian zone, and its economic implications.

Conserve biodiversity and ecosystems

- There is a need for improved understanding of genetic diversity of foundation river woodland species in Scotland, and the implications for sourcing trees for re-establishment of river woodlands, and therefore creating a strategic network of tree nurseries with native riparian species.
- Maps of native riparian woodland and floodplain woodland structure and composition (including tree species) for different regions and catchments and land use objectives are required for national efforts for the restoration of healthy riparian corridors in Scotland.
- Based on the national map of riparian woodland, tree nurseries for different tree species of riparian and floodplain woodlands should be set up to fulfil the need of future tree planting and river restoration projects.
- Further field-based evidence with controls is required to quantify the effect of native woodland expansion on biodiversity which includes river woodland networks.
- Further work is required on the impact and land required to accommodate rewilding. This includes understanding the interactions of large herbivores on river woodlands, their impact on riparian woodlands including ecosystem consequences and delivery of benefits.
- There is a need to identify a suitable focal species model for river woodland habitat [bird or bat/FWPM or aquatic invertebrate/lichen.
- Further research and development on SEPA's GIS analysis tool for determining space for morphological dynamic (including riparian vegetation width) is required. This should include validation of the sections identified by the GIS tool on site that allow for the prioritisation of reaches under different criteria.
- More research is required to further our understanding of landscape-scale nutrient recycling and to quantify the benefits that river and riparian species play within this (including fish).

Good human health

- More research to show specific health outcomes including psychological effects in a European context and for river woodlands more specifically.
- Further research is required to understand how best to design urban blue-green infrastructure involving river woodlands to optimise cooling for health benefits.
- Further research is needed to understand the impact of wooded riparian zones in Scottish cities on the urban heat island effect and health benefits.
- 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.

Wild fish and angling

- Further research is required to understand cooling, warming and insulating effects under different riparian canopies with or without the influence of groundwater discharge.
- 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.
- Further work is required to assess variability in invertebrate productivity, drift and salmonid diets between land-use types to better ascertain whether semi-natural riparian woodlands are able to support greater abundances and biomass of salmonids than more intensively managed land-use types. In a related area, further work is required to understand the complex interactions between food availability, competition (within and between fish species) and growth.
- Further research is required to understand the effects of large woody material on habitat and on the production of different native fish species.
- The development of predictive modelling work will be helpful to further understand how modifying habitat during restoration involving large woody material influences ecological interactions and subsequent impact on fish distributions and abundances.

Sustain food production

- Further work is required to understand the impact of livestock on different soils with recommendations for management of livestock under trees in different geographic settings (lowland, upland).
- The impact of the nutritional and medicinal benefits of tree fodder for livestock productivity requires further quantification in Scotland.
- Further research is needed to understand better the design of heterogenous landscapes (to include river woodlands) to optimise crop pollination.

Clean energy: biomass production

- Further work in Scotland is needed on understanding the benefits of short rotation coppice of river woodlands and its impact on water and soil quality.
- 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.
- Scottish based review of viability of biomass market from river woodlands including quantification of economic benefits to farm enterprises and assessment of local and regional demand for coppice and wood energy.

Annex 2: Enabling effective delivery of Riverwoods

Developing a business case

River woodlands will provide multiple benefits in any one location, sometimes called "benefit bundles". Some of the benefits may be easier to quantify than others, and different investors may be interested in specific benefits. The evidence of multiple benefits provided by particular locations need to be considered when river woodland restoration is packaged into investment ready projects. The business case for each Riverwoods project needs to identify the potential benefits and beneficiaries.

For example, the floodplain woodland immediately upstream of Callander in Loch Lomond and Trossachs National Park is:

1. Designated as a flood storage area, reducing flood risk to the community in Callander
2. A tourism hotspot in Loch Lomond and Trossachs National Park providing areas for picnicking, wild swimming, angling, walking and cycling,
3. Provides food, shade and protection for young fish fry - the river is a Special Area of Conservation for Atlantic salmon and three species of lamprey.
4. An area rich in biodiversity with the wet woodland and pools supporting amphibians.
5. A carbon store provided by the woodland, associated wetlands and large woody material.

There is evidence that riparian buffer zones combining woodland and wetland elements (also known as integrated buffer zones) can provide multiple benefits over relatively small surface areas compared with conventional grass buffers (Zak *et al.*, 2019). This is of economic interest for farmers, as it means that environmental goals can be met without disproportionally sacrificing land for crop production.

Business views about river woodlands

Land owning businesses views

The needs and motivations of different types of land owner and businesses also requires consideration as these might differ substantially: e.g. sporting estates, compared with community owned woodlands and other small-scale land/forest owners. The social acceptance or landowner acceptance of riparian woodland will be an important factor in driving planted woodlands, especially considering the ownership pattern. Surveys of land owner attitude on Highland estates found that riparian woodlands are viewed as "Adaptive forests". These are broadly categorised as those which exhibit diversified structure and species mix, which includes encouraging natural regeneration, planting small areas of mixed broadleaf species, and creating new forest corridors along riparian areas. Productive aims and management are notably absent from adaptive forest types, suggesting that adaptive forests are considered a low priority and something that belongs in the past on these sites (Bowditch *et al.* 2019). This could affect landowner attitudes to creating new buffer areas. Another land owner view communicated by an agency officer working with arable farmers is that wooded buffers are unacceptable to arable farmers as it blocks their field drains. Further work is needed to understand the views and attitudes of land owners alongside opportunity mapping based on technical factors and ownership.

Whilst interviews with landowners confirm that there is good understanding from land managers about carbon mitigation benefits and how it against alongside other objectives (e.g. Bowditch *et al.*, 2019). There is a need for improvements in communication about benefits: location specific information and how the benefits are measured at a local level need to be addressed (Bowditch E. Per Comm).

Non-land owning business views

Governance and business models to coordinate projects is another aspect to effective delivery of Riverwoods. For example, through interviews with businesses, land managers and the river trust on the Spey River in Scotland, Liski *et al.* (2018) found:

1. Businesses recognise the importance of natural capital to their business success, but this does not currently translate into significant investment
2. Businesses are interested in diversifying and increasing their investments in the environment, but find it difficult to identify tangible returns on investment
3. There is broad support for increasing coordination of investment through an independent business-led intermediary
4. Two potential business models for coordinated business investment were identified: a levy model and a project-based model
5. Government and public sector support are essential to increase investment

Both business models in this study highlight the importance of an independent and trusted agency to coordinate those wanting to invest, and the need for coordination and project management to work with land managers to enable effective delivery of project on the ground. A comprehensive review of investment mechanisms for natural capital projects has been undertaken by NatureScot (2021) [49] Further work is needed to quantify and monetise specific benefits from Riverwoods to help determine potential investment routes. However, the review provides a helpful starting point.

Fisheries manager's views

Fisheries managers work within Rivers Trusts and Salmon Fishery Boards in Scotland to manage rivers. This includes managing the riparian zone working with riparian owners. Therefore, understanding the views and attitudes of fisheries managers is key to successful delivery of Riverwoods.

Whilst there has not been research on the attitudes of fisheries managers to riparian woodland in Scotland, Marine Scotland Fisheries Scientists are aware of a range of views from their work with fisheries managers. Some fisheries managers are removing and thinning riparian woodland to open up more light to the river in order to increase food availability for salmon. Whilst others are planting trees to increase shade for salmon. Some have undertaken fieldwork that supports the case for bank side trees.

During the collation of evidence for this report we were directed to specific fishery managers who were undertaking adaptive management with supporting studies to understand the impact of their management. For example, Wester Ross Fishery Trust in the NW Scotland has found higher growth rates of salmon parr and smolts in rivers with bankside trees rather than without (*Peter Cunningham, pers. comms.)*. This is being linked to slightly higher nutrients and better food availability in these waters. Biological productivity in Wester Ross is believed by the Fishery Trust to be primarily limited by the availability of phosphorus (Cunningham, 2017).

The River Dee Trust is undertaking fieldwork on the inclusion of large woody material in rivers and its impact on salmon fish spawning habitat. The 137 large wood structures which have been installed in the River Gairn and River Muick in Dee-side are relatively recent in nature and will develop increasing complexity and ecological function over time. Edwin Third (Rivers Operation Manager for the River Dee Trust) states that:

[49] NatureScot Research Report 1260: Facilitating Local Natural Capital Investment: Literature Review

"Already we are seeing these LWS's creating suitable conditions for salmon spawning. 12 of the 40 structures installed on the Muick last year had salmon spawning adjacent to the new structures. These structures have also created areas of deep water and good cover under the root plates. So LWS's provide a complexity of flows, depths and bed materials which is exactly what salmon require during their complex life cycle. Although we are monitoring these structures it will take a few years for us to be able to provide meaningful ecological data, (apart from the obvious physical changes to the stream, which can be seen from the attached photo of one of the Muick LWS's). My view, having worked on the river Dee for 25 years is that salmon are at crisis point, and our rivers are far from pristine, we need to act now, monitor and then, if necessary, adapt our techniques, do more of what is shown to work, and cut out things that don't. We just don't have the time to only do small demonstration projects and monitor them in great detail for years".

There is a balance to be struck between adaptive management approaches that learn through trialling management change and scientific studies which ensure that there is scientific evidence based on changes to fish productivity and survival at a population level.

Farmer's views

Interviews with livestock farmers in the UK reveal that they recognise and value the shelter provided by trees and that shelter provision was a key objective for many farmers, with trees required to provide shelter from extremes of both cold and hot weather and act as wind breaks. According to the farmers, shelter reduces animal stress, which is linked to animal productivity which can lead to economic gains. Some farmers reported that using shelter during lambing reduces lamb losses. Riparian woodland was a component of shelter on the farms included in the survey, but their value was not separated out (Woodland Trust, 2017). A Shropshire-based dairy farmer has described the direct observed benefits of planting trees in awkward field corners (as well as in-field and hedgerow trees) (Woodland Trust, 2015[50]). The shelter provided helps to increase soil temperatures in early spring and late autumn, extending the grass growing season, as well as helping to mitigate wind speeds and the impact of hot, dry summers on pastures by improving crop water efficiency. As with most dairy systems, access to high quality grazing is essential, as higher nutritional values can lead to improvements in milk production. The farmer, Tim Downes explains how "Shelter from the trees now means that water is retained on the grazed land, meaning the cows now have access to more nutritious grazing because there is higher growth in the field."

Participatory approaches to engaging people

The Scottish Land-use Strategy (2011-2016) initiated trials of participatory approaches to decision making around ecosystem services at different scales. For example, the Strathard Initiative[51] in Stirling provides an example of this evaluation based on community input on which services they value and would provide future opportunity. It also provided simple to use evaluation tools for land managers to help understand the impact of land management options on multiple benefits provided in the catchment. The Aberdeenshire pilot[52] trialled participatory decision-making approaches at an estate and regional scale. It found that making decisions about land use in a more integrated and participatory way has clear benefits. However, the time and resources needed to work in such a way should not be underestimated. Building the capacity of both local communities and organisations (public and private) with regards to governance, knowledge and engagement is paramount if these

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[50] Woodland Trust (2015) Trees provide fodder and boost production case study

[51] More information about the outputs of the Strathard Initiative can be found here: Strathard Initiative project briefing July 2018 (sepa.org.uk)

[52] For more information about this trial see article on Approaches for more integrated and participatory decision making Ecosystem Services_web.pdf (hutton.ac.uk)

approaches are to be mainstreamed. These approaches could be adapted for use in Riverwoods initiative projects. Bowditch E. (*Per. Comm*.) recommends further exploration of a range of techniques to enable effective communication of benefits and delivery of river woodlands on the ground e.g. toolkits, interactive engagement resources, peer-to- peer sharing of experience, gamification, peer learning, and demonstration sites.

"Strathard - a landscape to live, work and play" is a partnership project which aimed to explore engagement with all stakeholders to influence how the land, forest and water within the area are managed. The project assessed many different opportunities for the people of Strathard to meet and inform agencies responsible for land management how the landscape affects their lives and tell decision makers exactly what the issues are for them.
An online mapping tool used to capture which parts of the landscape were most valued by the residents and visitors, reveals that the water margins of Loch Ard and Loch Arket are the most prised areas of the region.
(https://www.thecommunitypartnership.org.uk/project/strathard-a-place-to-live-work-play/)

Economic evidence

Stabilising riverbanks

An economic assessment of the economic value of the benefit that riparian woodland buffers provide by protecting adjacent plantation land from bank erosion has been undertaken in the Tropics. Using satellite imagery and a model of river channel migration, Horton *et al*., (2018) found that the cumulative economic losses from land and soil loss from bank erosion are higher in the absence of a forest buffer than when a buffer is left intact.

The economic value of the benefits that riparian woodland buffers provide by protecting adjacent productive agricultural land and soils from bank erosion has been undertaken in the tropics, but more work needs to be done in the UK and Scotland.

Cooling town & cities

One study attempted to model the evaporative cooling provided by the trees in three UK urban areas (Edinburgh, Wrexham and London) and how this translates into energy savings through increased air-conditioning unit efficiency. Trees are shown to provide substantial urban cooling with an annual valuation of £84 m estimated using the enthalpy-based approach, or ranging from £2.1 m to £22 m using dynamic simulation programs; both for inner London case study. The latter savings arose from a modelled 1.28–13.4% reduction in air-conditioning unit energy consumption (Moss *et al*., 2019)

Wild fish and angling

Wild fisheries and angling make a significant contribution to Scotland's economy. In January 2015 the Scottish Government, through Marine Scotland, commissioned PACEC to carry out an analysis of Wild Fisheries in Scotland covering salmon, trout and coarse angling and netting activities (mainly for salmon). Surveys estimated that 490,000 angler days were spent on salmon and sea trout fishing in Scotland in 2014. When all species are included, the study estimate that there were 1.3 million angler days in total in Scotland. In summary, the Scotland-wide economic impact assessment of wild fisheries (including netting) indicates around £135m of angler expenditure, 4,300 full-time equivalent jobs and £79.9m Gross Value Added (GVA) in 2014 – the monetary value of the contribution to the economy made by an industry[53].

[53] An Analysis of the Value of Wild Fisheries in Scotland (www.gov.scot)

Alleviating flood risk

In a strategic assessment of the flood regulation services provided in GB from our existing forest cover, Broadmeadow *et al.* (2018) used the JULES model and expert judgement to estimate the potential additional volume of flood water stored in existing floodplain woodland compared to an alternative grass cover. Using an average rise in rise in water depth of 52 mm, retained by the hydraulic roughness of floodplain woodland they estimate the current extent of Scottish floodplain woodland provide potential flood storage capacity for over 13 million cubic meters, which based on the average cost per m^3 for providing the same volume by constructing and operating a flood storage reservoir provides a flood regulation service of £5.7 million per year.

Design and restoration guidance

Healthy & Resilient River & Riparian ecosystems

Manual of river restoration techniques (RRC):
Manual of River Restoration Techniques | The RRC

Stream restoration:
Stream Restoration | NRCS (usda.gov)

Material to consider in riparian restoration (CONVERGES):
Resources Archive - Converges

Sustainable Riverbank Protection - Reducing Riverbank Erosion (SEPA):
Bank Protection Guidance (sepa.org.uk)

Rivers by design: Rethinking development and river restoration (EA):

LIT8146_7024a9.pdf (publishing.service.gov.uk)

Stage zero river restoration:
Welcome | Stage Zero (stagezeroriverrestoration.com)

Riverine Ecosystem Management: Science for Governing Towards a Sustainable Future: https://doi.org/10.1007/978-3-319-73250-3

Clean water

Measures to encourage the planting of riparian woodland buffers within agricultural and urban landscapes offer the greatest potential to benefit surface water ecology (Nisbet *et al.*, 2011):
Woodland for Water: Woodland measures for meeting Water Framework Directive objectives (forestresearch.gov.uk)

There are tools for identifying priority areas for strategic planting to target sources of pollution. Mapping to define the risk factors, pollutant sources and potential woodland habitat network can help guide site selection. In Scotland, constraint and opportunity mapping for woodland creation to deliver water quality (as well as flood risk mitigation) has been developed for the River Tay Catchment by Broadmeadow *et al.*, 2013:
Opportunity Mapping - Tay (forestry.gov.scot)

SCIMAP is a risk mapping tool that uses landscape properties (rainfall, topography, landcover type and hydrological connectivity) to determine the relative risk of surface erosion and delivery of sediment to the river network. If sediment fingerprinting has identified a catchment contributing a lot of sediment, SCIMAP can identify possible source areas within the catchment:
SCIMAP – Diffuse Pollution and Flood Water Source Mapping

QUESTOR (QUality Evaluation and Simulation TOol for River systems) is a daily river quality model which combines river flow and water quality data. It uses chlorophyll–a as a surrogate for river phytoplankton biomass. It is used to represent flows and chemical inputs to a network of river channels and test management scenarios against a baseline river system. It was used to test the effevctivness of planting riparian woodlands compared with other management solutions:
QUESTOR (Quality Evaluation and Simulation Tool for River Systems) - Catchment Management Modelling Platform (ceh.ac.uk)

PSI (Proportion of Sediment-sensitive Invertebrates, and the more recent E-PSI, can be used to assess the degree of deposited fine sediments on riverbeds. This metric, developed by Extence *et al.*, (2011), with further development (E-PSI) by Turley *et al.*, (2015) is a useful diagnostic tool:
https://doi.org/10.1002/rra.1569
https://doi.org/10.1016/j.ecolind.2015.02.011

Practical guidance available in SEPA Riparian Vegetation guide and River Restoration Centre guide:
WAT-SG-44 (sepa.org.uk)
Manual of River Restoration Techniques | The RRC

Forest Research Guidance on using woodland for sediment control (2004)
26497_For (forestresearch.gov.uk)

Environment Agency guidance on designing 3D buffer strips – designed to deliver more for the environment:
3D buffer strips: designed to deliver more for the environment - GOV.UK (www.gov.uk)

Environment Agency report reviewing of the positive and negative effects of woodland on the water environment Woodland for Water (2011):
Woodland for water - GOV.UK (www.gov.uk)

Climate action: alleviating flood risk

The design and management of riparian and floodplain woodland influences its effectiveness in slowing flows. This has been summarised by Ngai *et al.*, (2017)
Working with natural processes to reduce flood risk - GOV.UK (www.gov.uk)

JULES Model used for modelling floodplain woodlands:
Joint UK Land Environment Simulator (JULES) (jchmr.org)

Guidance for identifying opportunities for natural flood management:
SEPA’s Natural Flood Management Handbook
SEPA’s Natural Flood Management Maps

Opportunity mapping layers for strategic planting of trees for natural flood management:
Opportunity mapping for trees and floods - Forest Research
Forestry and Natural Flood Management - Forest Research

The Ciria Natural Flood Management Manual:
Item Detail (ciria.org)

Guidance on river floodplains and natural flood management on farmed land in Scotland:
tn646.pdf (sruc.ac.uk)

Climate action: carbon

Woodland Carbon Code provides carbon calculator tools and guidance:
Home - UK Woodland Carbon Code

Guidance on methods for biomass calculations are in the Carbon Assessment Protocol:
Carbon Assessment Protocol (woodlandcarboncode.org.uk)

Natural England carbon storage and sequestration by habitat – used for non- biomass calculations in Woodland Carbon Code:
Carbon Storage and Sequestration by Habitat 2021 - NERR094 (naturalengland.org.uk)

The Farm Advisory Service information on woodland creation and carbon sales:
Woodland Creation and Carbon Sales | Farm Woodlands (fas.scot)

Clean air

Centre for Ecology and Hydrology have developed guidance for farm woodlands to benefit air quality:
https://www.farmtreestoair.ceh.ac.uk/

i-Tree Eco version 6 is a flexible software application designed to use data collected in the field from single trees, complete inventories, or randomly located plots throughout a study area along with local hourly air pollution and meteorological data to quantify forest structure, environmental effects, and value to communities
i-Tree Eco | i-Tree (itreetools.org)

Sustaining soils

The UK Farm soils carbon code will consist of a set of formal protocols that allow farmers to quantify and verify reduced greenhouse gas emissions and/or soil carbon capture as a result of adopting regenerative farming practises:
Sustainable Soils News | All about Soil

Conserve biodiversity & ecosystems

Riparian woodland guidance: Parrott & McKenzie (2000). Restoring and Managing Riparian Woodland. Scottish Native Woods, Perthshire:
OUT.pdf (environmentdata.org)

Council Directive 1999/105/EC on the marketing of forest reproductive material for tree nurseries:
EU Directive 1999/105/CE.

Council Directive 2000/60/CE Water Framework Directive:
Directive 2000/60/EC)

Good health

Tool to support urban planning of blue spaces:
https://bluehealth2020.eu/projects/decision-support-tool/

Tool to measure psychological well-being: POMS Test (Profile of Mood States):
Profile of Mood States 2nd Edition™ - PsycNET (apa.org)

Wild fish & angling

Keeping Rivers Cool: A guidance Manual. Creating riparian shade for climate change adaptation:
keeping-rivers-cool.pdf (woodlandtrust.org.uk)

Models are available for targeting riparian planting at a national or regional scale and to inform local design (Marine Scotland)

A deterministic river temperature model to prioritize management of riparian woodlands to reduce summer maximum river temperatures - Jackson - 2021 - Hydrological Processes - Wiley Online Library

Prioritisation maps for planting for temperature moderation in Scotland are shown here and can be accessed via the NMPi (Scottish National Marine Plan Interactive) tool:
Scotland River Temperature Monitoring Network (SRTMN) – Riparian Woodland Prioritisation Scores | Marine Scotland Information

This website provides links to all the various mapping tools that we have made available through NMPi look at outputs and tools: Scottish National Marine Plan Interactive (NMPi) | The European Maritime Spatial Planning Platform (europa.eu)

Scotland River Temperature Monitoring Network:
Scotland River Temperature Monitoring Network (SRTMN) - gov.scot (www.gov.scot)

The National Electrofishing Programme for Scotland:
https://www.gov.scot/Topics/marine/Salmon-Trout
Coarse/Freshwater/Monitoring/ElectrofishingProgramme

Sustain food production

Managing woodland for pollinators:
Woodland Pollinator Sheet Final (buglife.org.uk)

Guidance on design and management for Aspen agroforestry:
Microsoft Word - Designing an Aspen Agroforestry Scheme Feb 2015 (eadha.co.uk)

Guide to developing a Woodland Grazing Plan for woodland owners, managers and farmers seeking to manage woodland to achieve biodiversity and or cultural heritage objectives, using livestock as a management tool:
Scottish Forestry - Woodland Grazing Toolbox

Guidance on river floodplain and natural flood management in Scotland on farmed land:
https://www.sruc.ac.uk/media/5abn0xqs/tn646.pdf

Wood pasture in Scotland:
ancient-wood-pasture-scotland.pdf (forestry.gov.scot)

Benefits of Agroforestry in Scotland and good practice advice and a case study:
Layout 1 (hutton.ac.uk)
Glensaugh Agroforestry Virtual Tour | The James Hutton Institute

The Farm Advisory Service provides advice and information on farm woodlands, including a dedicated farm woodlands newsletter:
Home - Farm Advisory Service | Helping farmers in Scotland | Farm Advisory Service (fas.scot)

The Woodland Trust Croft Woodlands advisory team helps crofters, smallholders and common grazings to create and manage woodlands:
Croft Woodlands - Woodland Trust - Woodland Trust

The Standards of Good Agricultural and Environmental Condition (GAECs) set Cross Compliance baseline requirements for farmers to safeguard soils, habitats and landscape features on their farmland:
Good Agricultural and Environmental Conditions (GAECs) 2022

Clean energy

The Agriculture and Food Development Authority and Agrifoods and Biosciences Institute provide best practice guidance for short rotation willow coppice:
Short rotation coppice willow best practice guidelines.pdf (afbini.gov.uk)

The UK Forestry Standard guidance sets out the governments' approach to sustainable forestry, including standards and requirements, regulations and monitoring and reporting:
The UK Forestry Standard: The governments' approach to sustainable forestry

Annex 3: Evidence on cross slope and catchment woodlands

River woodlands are a component of catchment woodlands and could bisect cross-slope woods, but cross slope and catchment woodlands are not river woodlands in themselves. The evidence for these types is included here as delivery of clean water and natural flood management benefits is more effective when in combination with woodland measures strategically placed within the catchment and a catchment approach is very important. Green financial investors will be interested in this evidence.

Definitions

Cross-slope woodlands: the placement of smaller areas or typically belts of woodland across hill slopes and includes all woodland types and species. It can be managed as either productive or unproductive woodland (Ngai *et al.*, 2017).

Catchment woodlands: defined as the total area of all woodland within a catchment, comprising general woodland cover of all types and species, including plantations, plus specific forms where present, such as cross-slope, riparian and floodplain woodland (Ngai *et al.*, 2017).

Clean water

Catchment woodland

There are numerous case-studies from the international literature that illustrate how afforestation and land-use change from agriculture to forestry provides watershed protection and can safeguard good water quality and essential drinking water supplies (Nisbet *et al.*, 2011). For example, the Drastrup Pilot Project in the City of Aalborg in Denmark was a public funded body catchment project involving the conversion of 900 ha of intensive agriculture into 500 ha of forest (natural broadleaved woodland) and 400 ha of pasture. This led to a decrease in nitrate concentration in groundwater decreased from less than 120 mg/l to less than 10 mg/l (in Nisbet *et al.*, 2011). In the UK, model simulations have been used to assess the effects of land use change scenarios on nitrate concentrations. In the Slea catchment in East England, protection zone model scenario simulations suggest a reduction in nitrate concentrations from >100 mg/l to below the regulatory 50 mg/l drinking limit (in Nisbet *et al.*, 2011).

Limitations & gaps in research

In the UK, field work involving afforestation including native riparian woodland at the catchment scale has focused on flood risk alleviation benefits without also quantifying the co-benefits. Long term monitoring research work at a catchment scale is required in Scotland to show the multiple benefits of restructuring and land-use change for watershed protection. Evidence for the multi-functionality of riparian woodland at the catchment scale is needed to inform and persuade regulators and land managers to implement effective nature-based solutions and devote greater resources towards this goal (Dittrich *et al.*, 2019). The Glen Oykel study in Sutherland led by Forest Research provides an opportunity for monitoring the long term effects of large-scale forest restructuring and land-use change on water quality and ecology. Objectives include investigating land-use change on nutrients, carbon and sediment transport.

Climate action: alleviating flood risk

Cross-slope woodlands

A cross-slope woodland is a woodland which is planted across a hill slope. It intercepts the flow of water as it runs down the hill reducing rapid runoff and encouraging infiltration and storage of water in the soil. In the headwaters of the Upper Severn in mid-Wales in the Pontbren catchment, observed data showed that soil infiltration rates were 67 times higher within woodland plots and shelterbelts planted on improved grassland compared with grazed pasture, which reduced run-off volumes by an average of 78% compared to control sites (Marshall *et al*. 2014). Peskett *et al*., (2020) found that cross-slope woodland strips in the Eddleston Water Catchment, a tributary of the River Tweed in the Scottish borders reduced soil moisture levels within the strips but not beyond 15 m downslope.

Both studies results provide evidence that cross-slope woodlands aid soil infiltration rates but this is not evidence for flood alleviation. However, the measured data at Pontbren has been used to develop and parameterise a physics-based, distributed run-off generating model which incorporates water use, soil infiltration and surface roughness processes. The field-scale modelling study suggested that planting tree shelterbelts near the bottom of all improved grassland fields in a 6km^2 sub-catchment might reduce peak flows by 13–48% for the largest storm seen in the study period (peak rainfall intensity 54mmh−1) (in Dadson *et al.,* 2017). For a hypothetical extreme storm with rainfall of 140mm over two days, the simulated reduction in peak flows was 2–11%.

Strength of evidence (based on quality of studies): Moderate.

Science confidence rating: Medium confidence at local scale but low confidence at the catchment scale due to the absence of measured data (Ngai *et al.,* 2017).

Limitations & Gaps in Research: Experts agree that there is a high level of uncertainty in scaling up (Dadson *et al*., 2017). Further work is required in understanding:

i/ the effect of a targeted and integrated network of cross-slope woodland across a range of catchment sizes for a range of flood events

ii/ the impact of cross-slope planting during a sequence of storm events

iii/ how the type of woodland, its placement in the catchment and the catchment's size affect its flood risk impact.

Catchment woodlands

There is strong empirical evidence to support the biophysical processes which enable trees to help with flood alleviation. This includes canopy rainfall interception (Nisbet *et al*., 2005), evapotranspiration (Brown, 2013), infiltration and soil water storage capacity (Marshall *et al*., 2014) and provision of surface roughness (Chow, 1959). Catchment woodland can intercept, slow, store and filter water due to these processes in play. Largest reductions in flood risk have been seen for small events in small catchments, the extent of this reduction decreases as flood magnitude increases (Ngai *et al*., 2017).

A systematic review (Stratford *et al.* 2017) on the influence of trees in flood peaks has shown that overall, the evidence suggests increasing tree cover decreases flood peaks and that decreasing cover increases flood peaks. Further distinction between observed and model-based studies and comparative results between the two types is less clear. Importantly, given the main summary, only modelled results were found to provide significant evidence that increasing cover reduces food peaks. The relative impacts of whether change in cover has variable impacts on the size of flood considered, is difficult to quantify and robustly consider given the lack of suitable information reported in the literature, but there is consistent and strong evidence that increasing cover reduces small floods.

Strength of evidence: Moderate

Science Confidence Rating: Scientific experts have concluded a high to medium confidence in the flood risk benefits of catchment woodland, because of the strong process understanding of the ways that woodlands reduce flood risk (Ngai *et al.*, 2017).

Limitations & Gaps in Research: Until recently established modelling software and techniques have not been able to simulate the impact of significant changes in vegetation coverage on catchment hydrological processes such as infiltration and run-off. Recent developments in modelling techniques including the modelling of complex pluvial and fluvial overland flow routes have enabled these processes to be modelled effectively (JBA Consulting, 2017). Southwell is located in a significant flood risk area and provides a good opportunity for assessing the effectiveness of woodland creation approaches. Model simulations to include the establishment of 150 ha of mature conifer woodland located in areas directly adjacent to key watercourses in the upper Halam and Potwell catchments in England for medium and larger flood events (25-75 year return period floods) showed a decrease in number of properties flooded. Further work includes applying the methodology to a wide range of catchments to test the appropriateness of the approach, further testing of flood events and storm durations. Also the methodology needs to be validated against observed data from woodland creation.

Combination of natural flood management approaches

Although it is very unlikely that floodplain woodland on its own would be able to provide complete protection for downstream towns or cities, it could make a valuable contribution alongside other natural and engineered flood management interventions, like leaky dams that are immediately effective. The increasing benefit over time as the trees mature means that it contributes to improving resilience to increasing flood risk due to climate change. Similarly, it could have an important role in helping to manage the frequent, small-scale, flood problems where the high cost of constructing hard defences cannot be justified. Despite the lack of robust empirical evidence and uncertainties at larger scales for the impacts of NFM (Dadson *et al.*, 2017), it is reasonable to assume that measures that offer some new available storage, slow runoff velocities whilst providing a range of wider ecosystem services (see Environment Agency, 2017) can be seen as positive for their other benefits (Wilkinson *et al.* 2019).

The *Slowing the Flow* project in Pickering, North Yorkshire saw the installation of 167 large woody debris dams within the Pickering Beck and River Seven catchments as part of a wider program of NFM interventions with the aim of protecting this small rural town from a 1-in-25 year flood (Slowing the Flow Partnership, 2016). These measures were guided by a modelling study (Odoni & Lane, 2010) which had identified suitable locations for various NFM interventions, which included LWD dams, riparian planting and restoration and the construction of two flood storage bunds. This project merits particular attention, as shortly after the construction phase had finished there was a large flood event (Boxing Day 2015) which, while outside the scope of the two official reports into the project, has subsequently been analysed and it has been shown that the NFM measures put in place reduced the peak flow by 15%–20% and did prevent flooding of a small number of downstream properties (Cooper *et al.* 2021). Due to the variety of mitigation measures in place at Pickering it is difficult to determine an individual measure's contribution to the peak flow reduction values.

The Belford Burn catchment (~6km2) in Northern England utilises observed data collected throughout the NFM project's monitoring period (2007–2012) introducing catchment-wide water storage through the implementation of runoff attenuation features (RAFs), including leaky dams, planting, sediment traps and offline storage areas as a means of mitigating peak flow magnitudes in flood-causing events. An experimental monitoring setup is introduced alongside an analytical approach to quantify the impact of individual offline storage areas, which has demonstrated local reductions in peak flow for low magnitude storm events. A physically based model has been created to demonstrate the impact of a network of offline storage areas to enable assessment of storage thresholds required to mitigate design storm events, thus enabling design of an NFM scheme. The modelling results have shown that peak flow can be reduced by more than 30% at downstream receptors, but it is difficult to know the contribution of each of the measures, it is reiterated that the RAF approach promotes the use of a network of features distributed throughout the catchment (Nicholson *et al.* 2019).