NATURE-BASED SOLUTIONS FOR CLIMATE CHANGE IN THE UK

A REPORT BY THE BRITISH ECOLOGICAL SOCIETY

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The British Ecological Society is the largest scientific society for ecologists in Europe. We are working towards a world in which nature and people thrive, and we do this by supporting new ideas, increasing the impact of our science and being an inclusive home for everyone in ecology. Our policy work brings together the best ecological evidence available and develops recommendations to aid effective policymaking. Ecology is providing the evidence we need to halt losses in nature and mitigate the effects of climate change. This is crucial for our world and for our wellbeing and prosperity.

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FOREWORD

We live in a time of immense environmental challenge and opportunity. There is a pressing need to stabilise our rapidly changing climate within a few decades and also to halt and reverse the precipitous decline of so much of the natural world and its biodiversity, while at the same improving the lives of many who live in deprivation and poverty. Yet there is new and real momentum in attempting to address these challenges at levels ranging from international and national policy through to bottom-up actions by cities, civil society, local communities and landowners. In the UK, as in many other countries, the COVID lockdowns have led to new appreciation of how important local nature is to our individual and collective wellbeing. The desire to "build back better" after the COVID pandemic, together with a radical new rethinking of land use policy and incentives, has led to a burst of interest and creative thinking about how the landscapes and ecosystems of this biodiversity-depleted country can be better managed to facilitate biodiversity recovery and contribute towards addressing climate change, while also providing for the welfare and livelihoods of local communities

The concept of nature-based solutions (NbS) to climate change encapsulates this new opportunity and synergy between the climate change, biodiversity and societal agendas. For this report we employ the definition of NbS as solutions that "work with and enhance nature to mitigate or adapt to climate change while simultaneously providing benefits to biodiversity and people". Nature can be our ally in tackling both climate change mitigation and adaptation, through processes such as carbon sequestration, greenhouse gas emissions reduction, flood risk reduction, ecologically connected landscapes and better urban environments.

This report by the British Ecological Society makes a valuable contribution to this agenda by providing an authoritative review of the potential of NbS in the UK. It examines a range of ecosystems and land uses and also looks at wider considerations of what it would take to deliver nature-based solutions at sufficient scale, including policies and potential trade-offs. It draws on the collective expertise of around 100 contributors with a wide range of expertise, and is a wonderful example of how the broad ecological community of academia, research, civil society and practice can pool its expertise and insights to make an important contribution to this timely and pressing issue. This report was written based on the expertise of the BES membership community; the authors and reviewers are largely academics from the field of ecology, as well as scientists and practitioners from statutory agencies and NGOs.

When thinking of NbS, tree cover and woodland restoration tends the get the limelight, but, importantly, this report shows how an NbS approach can apply to a wide variety of ecosystems ranging from high peatlands to grasslands, heathlands and agricultural and urban environments, through to freshwater, coastal and marine systems. It also highlights that it is important not to focus on carbon sequestration as the only goal, as this can result in negative biodiversity outcomes such as monoculture plantations, or tree planting on species-rich natural grasslands or heathlands.

The second part of the report looks at broader issues around the implementation of nature-based solutions in the UK, such as what policy, governance and finance frameworks, as well-as systemic change, are needed to deliver these solutions at sufficient scale while also engaging effectively with local communities and other stakeholders. Nature-based solutions need to deliver for societal and human wellbeing as well for nature and climate. Given the expertise of members of the BES, this report focuses mainly on the biodiversity and climate change aspects, while fully acknowledging the equally important benefits of NbS to people's health and wellbeing.

A big thank you to the all the contributors for their dedication, hard work and insightful contributions, and to the British Ecological Society Policy Team for their convening and production of this report, and skillful navigation and synthesis of the many complex issues that it covers. I truly believe it will be a landmark in setting the agenda and scientific and policy framework for the roll-out of nature-based solutions in the UK, and thereby to our collective aspiration to build a vibrant, resilient and resurgent natural world and stable climate in which our society and communities can thrive.

Professor Yadvinder Malhi CBE FRS
President-Elect, British Ecological Society

Yadvinder Malhi, Wytham Woods © Debbie Rowe

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EXECUTIVE SUMMARY

INTRODUCTION

Nature-based solutions (NbS) address societal problems in ways that benefit both people and nature. The main focus of this report is the joint role of NbS for addressing the climate and biodiversity crises we currently face. Natural habitats act as NbS for climate if they sequester carbon (contributing to Net Zero targets) or provide adaptation to climate change effects (for example, reducing flooding, protecting coastline against sea-level rise or creating cool spaces in cities). As well as these climate benefits, they can enhance biodiversity, create improved and more resilient ecosystem functioning, enhance human wellbeing and provide economic benefits, in terms of monetary value and job creation. Despite the huge range of benefits NbS have, they should be seen as complementary to other climate and conservation actions, not as a replacement to them.

This Executive Summary provides five key themes which emerge across the report, across the multiple habitats and multiple NbS studied. Six 'priority' habitats for NbS are given at the end of the summary. However, we emphasise that all habitats covered in the report can act as NbS and all can play a role in addressing the climate and biodiversity crises.

FIVE OVERARCHING THEMES:

1. NATURE-BASED SOLUTIONS FOR CLIMATE AND NATURE

NbS enable nature to help resolve the problems of climate change, both in reducing atmospheric greenhouse gas concentration and adapting our infrastructure. They are not a panacea for meeting Net Zero by 2050 and cannot be seen as a substitute for the significant emissions reductions across other sectors that are needed to meet this goal. Some NbS, such as peatland restoration are valuable because they reduce emissions. Other NbS can help to offset emissions that cannot feasibly be reduced by economic, behavioural or technological change. It is essential to implement NbS at a large scale to deliver sufficient benefit for climate change mitigation.

NbS can also help us to adapt to climate change, not least in reducing flood risk and protecting coastal communities from rising sea levels and storm surges. Many ecosystems, including rivers, wetlands and woodlands, are themselves vulnerable to climate change, and action will be needed to facilitate their adaptation if they are to provide NbS in return.

Strategic and well-executed NbS will simultaneously provide significant additional public goods. This includes biodiversity benefits that could help drive the delivery of conservation targets and also benefit people's health and wellbeing. Potentially perverse biodiversity outcomes need to be recognised and avoided, including the loss of high-biodiversity, low-carbon habitats (see *theme 4* below).

NbS should seek to maximise outcomes for climate, biodiversity and people. Any intervention that has an overall negative impact on one of climate, biodiversity or local communities, even if beneficial to other areas, should not be considered a NbS.

Key message: NbS can make an important contribution to Net Zero, biodiversity and climate change adaptation targets, so long as they are not treated as a substitute for widespread emission reductions or wider nature conservation action.

2. NATURE-BASED SOLUTIONS FOR HEALTH AND PROSPERITY

In the wake of COVID-19, NbS can be particularly effective in stimulating 'green' employment in the short term and supporting sustainable economic growth in the medium term, forming part of a green approach and investment to economic recovery. Nonetheless, delivering NbS at the scale necessary to make a significant difference will require state investment as well as changes in the legislative and policy architecture to encourage private investment. Clear markets beyond corporate social responsibility need to be identified and developed for which the state will need to maintain an active role. The environmental and financial benefits of private investment also need to be carefully monitored.

Spending time among nature can boost human health and wellbeing, which became particularly apparent during the recent pandemic as more people spent time in nature, benefitting from its restorative effects.

The human health and wellbeing benefits derived from NbS are of additional and widespread value to the benefits delivered for nature and in addressing climate change. However, given the expertise of the majority of British Ecological Society members, human health and wellbeing aspects of NbS have not been evaluated in detail in this report.

Key message: NbS provide human wellbeing and economic benefits. Routes for private investment alongside public finance are emerging but need further development.

3. GETTING THE RIGHT FRAMEWORKS AND POLICIES IN PLACE TO DELIVER NATURE-BASED SOLUTIONS AT SCALE: A WINDOW OF OPPORTUNITY

Each nation of the United Kingdom is currently developing many post-European Union policies. This creates a window of opportunity to ensure that cornerstone policies and legislation for the environment, society and economy enable the delivery of effective NbS at scale. Ambitious post-Brexit proposals, combined with long-term targets (e.g. Net Zero for greenhouse gas emissions by 2050) can create a favourable environment for adopting NbS and for stimulating private and public investment.

With foundations in both nature and societal outcomes, NbS require a broad policy and governance scope, and shared knowledge resources. Multiple interests are involved in the governance of NbS across a variety of scales and there are challenges associated with working across different policy areas, as well as generating effective partnerships. We recommend a working group or groups to assess both the opportunities, and the existing policy and governance frameworks, to deliver NbS.

When delivered at scale, NbS actions often have to be coordinated across whole landscapes and have local 'buy-in' for their success. Achieving collaboration requires mechanisms that can build the necessary social capital and help normalise NbS environmental management within the land/marine management community, and in the local community and societal beneficiaries of NbS. In both these broad sectors, there may be a wide range of attitudes towards biodiversity and its management as well as to the requirements and means of climate change adaptation and mitigation. New and novel NbS projects require knowledge exchange and collaborative ways of working. With a mix of private and public interests, state involvement in governance structures can be vital for the effectiveness of NbS and enforcement of regulations.

An assessment framework is needed for NbS that enables transparent assessments at multiple spatial scales and can be utilised by all key stakeholders. Agreeing clear outcomes and benefits for nature and climate change at the inception of NbS projects is vital to successful monitoring and assessment. Assessment frameworks may need to be a multi-phase process to incorporate assessments at the range of scales required for NbS initiatives. Successfully assessing adaptation may be made difficult by lack of a 'control' situation and by difficulties in attributing impacts to climate change. Existing assessment frameworks, such as the Strategic Environmental Assessment Regulations and the Environmental Impact Assessment Regulations, should be evaluated and adapted to ensure they are able to assess NbS initiatives. There is also an overarching need to ensure that policies across different sectors work well together across multiple interests and deliver the multiple benefits of NbS.

With the right frameworks in place to underpin NbS, they can make a significant contribution to national and international commitments. Long-term policies, goals and government commitments are necessary however to support long-term investment, research and monitoring of the functionality of NbS, as well as their delivery.

Key message: NbS opportunities and delivery approaches are evolving, and policy, governance and evaluation methods need to develop to encourage uptake and achieve the benefits.

4. GETTING THE RIGHT NATURE-BASED SOLUTIONS IN THE RIGHT PLACES

Strategic spatial planning and detailed project plans are necessary to integrate NbS with land use and ensure both biodiversity and climate benefits. It is also essential to address any trade-offs and avoid perverse outcomes. This requires the right data, diagnostic tools and the capacity and expertise to interpret and find solutions for all objectives and desired outcomes. This will require an increase in present capacity, including in the public sector, both nationally and locally, with many local authorities lacking the resources to employ ecological and environmental specialists. An appropriate multi-stakeholder and multi-level governance framework can help overcome existing resource and skill deficits by combining public and private sector input, but must ensure independence of assessments from narrow sectoral interests.

NbS may involve the substitution of one habitat for another, so it is vital to understand factors such as underlying soil conditions, habitat quality and potential biodiversity losses and gains, to ensure positive outcomes. For instance, woodland creation on some species poor, low productivity grasslands may be a good NbS for climate change mitigation. However, on a species rich grassland it could damage biodiversity and where grassland is found on degraded peat soils, restoration by re-wetting is likely to have better NbS outcomes for biodiversity and greenhouse gas reduction. Good spatial datasets can help with targeting but, in many cases, site specific environmental assessments for NbS initiatives will need to be conducted by suitably qualified experts to ensure the appropriate beneficial outcomes for nature that NbS require.

Effective planning for NbS at appropriate spatial scales can also help to capitalise on the co-benefits that can be delivered by NbS. For example, tree planting is an effective method of carbon sequestration and if strategically planned, tree planting alongside rivers has the potential to sequester carbon, reduce flood risk, stabilise river banks and also cool water temperature for vulnerable species. Currently planning systems in the UK are fragmented with multiple policies and bodies governing different sectors within a geographic area. Existing governance structures do not therefore lend themselves to the strategically designed and cross sectoral approaches that successful NbS delivery often requires.

Cities and urban areas face a multitude of competing interests and challenges and it is particularly important that NbS have clear co-benefits there to attract funding and bring a range of benefits to these environments and their inhabitants. The recent pandemic has reminded us of the importance of access to green space and the wellbeing benefits of nature. This has been particularly pronounced in urban areas and has also shone a light on unequal access to nature. Implementing NbS will benefit from appropriate socio-economic data to ensure, for instance, that NbS are helping to redress both environmental and social inequalities.

A variety of landscape-level planning approaches relevant to NbS exist or are emerging. These include the Ecosystem Approach, Local Plans, Local Natural Capital Plans, Catchment Management Plans, Landscape Enterprise Networks, the Nature Recovery Network and Local Nature Recovery Strategies, Local Nature Partnerships (LNPs), Farmer Clusters and forthcoming environment and green growth strategies across the UK. These participatory, interdisciplinary and evidence-based approaches aim to balance conservation of biodiversity and the sustainable use of natural resources with fair and equitable sharing of the benefits and also the potential to contribute climate change solutions.

Key message: The multiple benefits of NbS require careful spatial and project planning to deliver multi-sectoral benefits.

5. GETTING THE RIGHT EVIDENCE FOR NBS

Knowledge and evidence about the opportunities and effectiveness of different NbS interventions is lacking. For example, techniques for measuring carbon sequestration are well established in a research context, but differ between habitats and, often with a site-specific context, are rarely used for evaluating wider environment management or large-scale monitoring and surveys. This affects our ability to incorporate NbS into project-based carbon accounting – which may hamper the use of carbon credit finance, if site carbon fluxes cannot be measured or accurately estimated.

Key research gaps are summarised in *Appendix 2*. Examples include the relative benefits of natural woodland regeneration versus afforestation as a NbS, and what the appropriate management standards are for the latter. The criteria and standards required for an activity to be deemed as NbS must be clear and strengthened to ensure that projects deliver climate, biodiversity and human benefits.

Applied research across disciplines will be key for NbS innovation and evaluation. Whilst this may attract some private funding, strong government funding will be necessary, including to provide assurance of independence from vested interests.

It is also necessary to overcome barriers often experienced in getting scientific research accepted, understood and translated effectively into policy and practice. This includes the use of academic vocabulary by ecologists and conservationists, the promotion of tools and models that are complex and difficult to understand, and failure to capture the inherent value of nature in economic models. Characteristics of scientific assessments that have successfully influenced policymaking include a multi-disciplinary approach, involvement of decision makers and other stakeholders in the assessment process, a clear statement of the implications for human wellbeing and effective communication, both directly and indirectly via the media, for example, with decision makers and the public.

Key message: There are knowledge gaps and uncertainties which hamper the more wide-spread use of NbS. These knowledge gaps are a barrier to developing the full potential of NbS for climate, nature and people.

EFFECTIVE NBS FOR DELIVERING BIODIVERSITY AND CLIMATE CHANGE BENEFITS

The following table summarises effective NbS identified in the report where there is a good degree of confidence in the available evidence. A number of other habitats and NbS have been explored in detail and gaps in research have been highlighted, although it should be stressed that all NbS are important and should be considered as part of a broad portfolio of projects. For executive summaries of each chapter, please see *Appendix 1.*

NbS/Habitat	Climate change mitigation potential	Climate change adaptation potential	Biodiversity potential	Specific policy recommendations
Peatlands	Peatlands store around 3 billion tonnes of carbon in the UK but are emitting an estimated 23 million tonnes of carbon dioxide equivalent (CO2e) annually (c. 5% UK emissions) as a result of drainage and degradation. Restoration can reduce and eventually halt these emissions.	Peatland can help slow water flow during storms. Restoration reduces peatland vulnerability to climate change.	Restoration can help re-establish rare species and distinct peatland biodiversity on extensive areas of degraded habitat.	Restore degraded peatlands; drainage should be stopped and reversed. Continue to develop Peatland Code and public financing. End burning on blanket bogs.
Woodlands	The UK's forests currently store around 1.09 billion tonnes of carbon and sequester about 4.6% of the country's total emissions. They currently cover 13% UK land area and there is scope to increase this significantly.	Woodlands can provide adaptation through reducing flood risk, and provide shade and cooling in rural and urban settings.	New native woodland will increase woodland biodiversity and robustness to climate change. Increasing woodland connectivity will also benefit biodiversity.	Successful woodland NbS requires specific spatial and ecological planning. Avoid species rich grasslands, peat and other organic soils. Increase native woodland area, increase connectivity, and encourage natural or assisted regeneration of native species.

NbS/Habitat	Climate change mitigation potential	Climate change adaptation potential	Biodiversity potential	Specific policy recommendations
Saltmarsh	Establishment of saltmarsh habitats will provide sequestration and burial of carbon from local, marine, freshwater and terrestrial sources in saltmarsh sediment.	Saltmarshes provide coastal protection from sea-level rise and storms.	Saltmarsh provides a high biodiversity coastal habitat especially for many bird species.	Establishment of more saltmarsh, as proposed in existing shoreline management plans and Climate Change Committee targets.
Arable Landscapes: Hedgerows and Field Margins	High soil carbon levels are found under and adjacent to hedgerows and in field margins.	These areas improve water infiltration into the soil store storm runoff. They can prevent soil erosion, and capture pollution (e.g. fertilizer).	13 Section 41 bird species use hedgerows as primary habitat. Hedgerows have rich biodiversity, including high levels of plants, fungi and invertebrates, including pollinators. These habitats increase ecological connectivity. The high biodiversity in these habitats enhances pest management of adjacent crops.	Ensure protection and re-establishment of hedgerows. High-priority for future post-CAP environmental payments across the UK.
Arable Landscapes: Agroforestry	Agroforestry provides carbon sequestration and storage with average storage estimated to be up to 63 tonnes of carbon per hectare due to increased presence of trees.	Agroforestry provides adaptation through reduced flood risk, microclimate benefits and prevention of soil erosion.	Agroforestry provides increased biodiversity due to tree cover and hence habitat for many species including invertebrates and birds.	New public and private land management funding should incentivise a significant increase in agroforestry.
Urban Street Trees	Increased carbon sequestration from tree growth and habitat creation (small compared to national carbon budget)	Trees provide a localised cooling effect; estimated to save £22 million in annual energy consumption across inner London for example. Trees enhance recreation and connection to nature.	Increased numbers of trees provide increased biodiversity through enhanced green spaces, and increased connectivity.	Increase urban green space and features across urban policy sectors including planning, amenity, recreation and health, with focus on native species to ensure NbS.

CLOSING STATEMENT

NbS have great potential to tackle the two defining crises of our age. This report provides examples of opportunities for NbS across a range of habitats, as well as discussion of some of the complexities involved in planning for NbS. The report also outlines a detailed analysis of the tools, financial mechanisms and policies required for effective delivery in a UK context. Policy change will be necessary to overcome some of the challenges associated with NbS and to ensure that they fulfil their potential, yet the rewards are vital in meeting national climate change and biodiversity targets.

INTRODUCTION

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1. NATURE-BASED SOLUTIONS

1.1 DEFINITION

Nature-based solutions (NbS) is an umbrella term that brings together a diverse range of stakeholders and disciplines into collaboration, resulting in transdisciplinary work and a range of differing perspectives[1,2]. The International Union for the Conservation of Nature (IUCN) defines nature-based solutions as "actions to protect, sustainably manage and restore natural and modified ecosystems in ways that address societal challenges effectively and adaptively, to provide both human well-being and biodiversity benefits. They are underpinned by benefits that flow from healthy ecosystems and target major challenges like climate change, disaster risk reduction, food and water security, health and are critical to economic development."[3]

We recognise that NbS is a broad concept and can provide multiple benefits. For the purposes of this report, we have taken a narrow focus on the benefits for biodiversity, climate change mitigation and climate change adaptation. This is due to the objectives of the BES and the expertise of our members. Whilst the exact definition of NbS can vary between organisations and within literature (as shown in Annex 1 to this chapter), at the core of the concept is the multi-functional benefits that can be derived from using nature as a solution to a range of problems.

1.2 MULTIFUNCTIONALITY AND THE CONCEPT OF NATURE-BASED SOLUTIONS

Over the last decade, policymakers have increasingly recognised the importance of protecting nature not just for its own sake but also for the many benefits it provides for people. It has become clear both that protecting and restoring nature can increase its resilience to anthropogenic changes and help people mitigate and adapt to environmental change[4].

The approach of utilising nature as a solution is grounded in the relationship between biodiversity and ecosystem function. Living organisms interact with other each other and the physical environment in ways that maintain ecosystem function and species themselves[5]. Ecological interactions depend on a sufficient number of individuals and their chance of co-occurrence. The loss of these interactions leads to the loss of ecosystem functioning[6]. Change in the physical environment, for example with drainage, can also change what species survive in a place. All of these factors combine to affect ecosystem processes, such as carbon sequestration and water flow.

Greater levels of biodiversity often results in higher levels of ecosystem functioning and greater stability[7,8]. Of these ecosystem functions, many directly or indirectly benefit humans, and these are termed 'ecosystem services'[9] e.g. pollination, water cycling and carbon sequestration. The potential of NbS to solve wider societal challenges opens up new opportunities for mainstreaming biodiversity conservation into policy and practice decisions in other sectors and areas of society[10,11,12].

NbS are based on the understanding that ecosystems naturally provide ecosystem services. Therefore the protection, sustainable management and restoration of ecosystems can protect and enhance the provision of these services[13]. However, it is important to recognise that NbS alone are not a panacea for climate change and biodiversity loss. They are an essential component of responding to climate change but must be implemented alongside other efforts across society to reduce emissions, adapt to climate change, and reverse the decline in biodiversity[13,14].

2. CONTEXT AND RATIONALE

2.1 UK POLITICAL ENVIRONMENT

The United Kingdom (UK) has committed to reach net-zero greenhouse gas (GHG) emissions by 2050[15] and is a signatory to the UN Framework Convention on Climate Change (UNFCCC) and the Paris Agreement[16]. The Net Zero commitment derives from analysis by the Intergovernmental Panel on Climate Change (IPCC), following the signing of the Paris Agreement, which found that achieving the goal of limiting warming to 1.5°C required global net anthropogenic CO2 emissions to decline by about 45% from 2010 levels by 2030 and reach 'net-zero' by around 2050[17]. There are a range of other international commitments, including the United Nations Sustainable Development Goals (SDGs) and the Convention on Biological Diversity (CBD), which also commit the UK to tackle both the climate and biodiversity crises. To achieve these targets and to make effective strategic decisions, it is necessary for policymakers across the nations of the UK to have access to relevant and reliable evidence regarding potential solutions that are relevant for their specific contexts and political landscapes. The upcoming UNFCCC 26th Conference of the Parties (COP 26) has added urgency for this information to be available with an additional emphasis on delivering a 'Green Recovery'[18] from COVID-19.

Following the UK's exit from the European Union, there are new opportunities to address climate change and biodiversity loss through the implementation of innovative policies. For example, leaving the Common Agricultural Policy (CAP) has created an opportunity to move public monetary support for agriculture away from area-based support. This creates additional resources for mechanisms with greater potential to provide multiple benefits to society and the environment, such as NbS. For example the development of new subsidy frameworks for delivering environmental 'public goods' under Environmental Land Management Schemes (ELMs) in England[19]. This could provide opportunities for farmers, foresters and other land managers to secure financial reward in return for delivering environmental benefits. New agri-environment schemes are also being developed by the devolved governments[20].

2.2 CLIMATE CHANGE TRENDS

Climate change is a global issue. The atmospheric concentration of GHGs has grown at unprecedented rates since the beginning of the Industrial Era[21], with dominant causes including fossil fuel burning and land use change, such as deforestation[22]. Increased GHG concentrations have enhanced the natural greenhouse effect, resulting in the global mean temperature increasing by 1.2°C since pre-industrial times[23].

In the UK, the annual average land temperature in the most recent decade (2009-2018) has been 0.9°C warmer than the 1961-1990 average[24], and the frequency of heatwaves has increased[25]. There are also changes to rainfall patterns, which have led to increased flash flooding and droughts[26,27,28,29] across different localities. This may result in shortages to water supply[30], with downstream implications on human health and agricultural production[31]. Since the start of the 20th century UK sea levels have risen by 16cm.[32] It has been estimated that combined, these changes pose substantial risk to the nation as well as to communities[33,34], with 1.8 million people across the UK currently living in areas of significant flood risk. There are also 2.6 million people projected to be living in areas projected with risk by the 2050s[35]. NbS alongside other efforts can play an important role in helping the UK to mitigate and adapt to some of the effects associated with climate change.

2.3 BIODIVERSITY TRENDS

The recent Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) report classified 25% of assessed species as threatened[36]. In the UK, the State of Nature Report described a 13% decline in average abundance of species and a 5% decline in average species' distribution of terrestrial and freshwater species since 1970[37]. It was also found that the key pressures on biodiversity come from agricultural management, climate change, pollution, urbanisation, woodland management, land use change and invasive species[37].There is recognition across UK governments that we need to reduce environmental pressure and put people at the heart of biodiversity conservation[38,39,40,41].

Climate change has been identified as a key driver for biodiversity loss[42,43,44,45]. It has also led some species to change the timing of their seasonal lifecycle patterns, distribution shifts and local population changes[46,47,48]. Whilst some species can persist or adapt to climate change, others may go extinct[49,44,50,51,52]. Adaptation and building resilience of ecosystems will play an increasingly important role in reducing the loss of UK flora and fauna by helping habitats and species (e.g. Natural England and RSPB 2020)[53] to respond to climate change. For example, greater habitat connectivity and/or better-quality habitats can make species more resilient to change, as can the careful restoration of habitats or enhancing biodiversity hotspots[54]. These measures can also facilitate change to new conditions. Actions to protect biodiversity from climate change need to be integrated with NbS, both to ensure NbS are resilient to climate change and maximise benefits to biodiversity.

2.4 EXAMPLES OF HOW TO ADDRESS CLIMATE CHANGE AND BIODIVERSITY LOSS THROUGH NBS[1]

Climate change mitigation can be achieved via NbS by[55,47,56,57,58]:

- Reducing carbon emissions, e.g. avoiding deforestation and restoring degraded peatland.
- Increasing carbon sequestration in ecosystems, e.g. reforestation, peatland restoration and agroforestry.
- Increasing carbon sequestration in human communities e.g. Urban tree planting (ensuring the careful selection of the site and species of tree and making sure the species is resilient to climate change and other long term effects are considered.)

[1] Not an exhaustive list, examples are based on the specific scope of our report.

Climate change adaptation can be achieved via NbS through a variety of measures including[13]:

- Saltmarsh restoration which provides coastal flooding protection.
- Re-naturalisation of water courses and wetland restoration to provide natural flood management in river systems
- Cooling the urban environment, e.g. green roofs or green spaces.

Benefits to biodiversity can be delivered via NbS through:

- Identifying biodiversity hotspots, e.g. protecting the 2% of species rich biodiverse grassland we have left in the UK.
- Habitat restoration and habitat creation, e.g. peatland restoration, green roofs in urban settings or seagrass and kelp in marine habitats.
- Managing change and building in resilience, e.g. increasing the genetic and species diversity within ecosystems or adopting strategies such as integrated pest management practices.

2.5 HUMAN HEALTH AND WELLBEING

Human health and wellbeing are also benefits that can be derived from NbS. However, given the objectives of the BES and the expertise of the majority of our members, the human health and wellbeing aspects of NbS have not been comprehensively evaluated as part of this report. Nevertheless it is important that NbS are embedded holistically within a wider framework of societal, economic and environmental policies that together will result in multifunctional beneficial outcomes.

It is increasingly recognised that nature is an asset to humans[59,60]. There is a wealth of research on how observing and engaging with blue surface water (i.e., lakes and coastal waters); and green terrestrial areas (i.e., forests and parks), referred to as Blue Health[61] and Green Health[62], can benefit the health and wellbeing of all age groups[63,64,65]. Contact with the natural world allows the synergistic benefits of physical activity and nature contact to buffer poor psychological health by allowing mental recuperation[66,67,68] whilst promoting low-level activity for good physiological health. Engaging with nature has been found to provide people with life satisfaction and wellbeing benefits[69] through reduced mental health illness[70,71] and improved in social connectedness. A connection to the natural world can provide a sense of belonging and buffers the feeling of ostracism through improving emotional wellbeing[72,73]. There is growing evidence that people who have the opportunity to care for nature, such as feeding garden birds, felt more relaxed and a sense of oneness due to caring for the welfare of organisms as well as providing opportunities to socialise[74,75]. Consideration of the quality of the green space, in addition to the quantity, can produce multiple benefits for people and the environment[76].

3. SCOPE AND LIMITATIONS

3.1 SCOPE OF THE REPORT

This report presents an overview of the best scientific evidence available to assist in the understanding of the delivery potential of NbS for climate change mitigation and adaptation as well as for biodiversity conservation in the UK. Some chapters have also highlighted where further research is required, (for an overview of this please see Appendix 2 of this report). The report focusses on the UK evidence and draws on international evidence that is relevant where UK evidence is limited. This report is intended to inform policy makers, landowners and investors.

The report is divided into ten chapters and two sections. Section 1 has eight habitat chapters. Each chapter contains an executive summary (for an overview of this please see Appendix 1 of this report), definition of the theme, climate mitigation potential, climate adaptation potential, biodiversity value, relevant challenges and trade-offs. Some chapters demonstrate the benefits for human wellbeing. Section 2 of the report is not habitat specific and covers wider considerations for delivering NbS in the UK such as, policy and finance and the spatial delivery.

3.2 LIMITATIONS OF THE REPORT

We are fortunate that our members have a wealth of expertise in biodiversity and climate change mitigation and adaptation which is what we have drawn on for the purposes of this report primarily. There are nonetheless significant gaps in the underlying evidence which we have identified. We have also focused on presenting the evidence and options rather than advocating specific policies.

4. PROCESS AND METHODS

4.1 PROCESS

The BES Policy team issued a 'call for expertise' to our membership on this topic. This received responses from over 100 interested experts. Lead author(s), contributors and reviewers were found for each chapter based on experience, fields of expertise and relevance to the UK-context.

In order to ensure the chapters were reviewed robustly, those who reviewed the chapter were not involved in any of the stages of writing the chapter. The length and content of each chapter reflects the habitat type and the availability or gaps that are present in the evidence.

4.2 STANDARDISATION OF CARBON SEQUESTRATION FIGURES IN THIS REPORT

Reporting on carbon sequestration is a relatively new process, and standardised methods, measurements and units are not readily available or consistent in the scientific literature. Most commonly reported is a mass of sequestered carbon dioxide, per unit area, per unit of time, and these have been presented as tonnes of carbon, per hectare per year within the report (t.CO_2/ha/yr). Where alternative measures such as tonnes of carbon dioxide equivalent have been reported, these have been standardised into t.CO_2/ha/yr for direct comparison.

We have followed the scientific literature carefully, including examining the methods sections of papers to ensure as much consistency as possible, but while comparisons within chapters should be robust, comparisons between chapters and between different habitats may be susceptible to some differences in approach in measuring these values. There is clearly a need for a standardisation of approaches to measuring and reporting carbon sequestration across habitat types, especially if NbS are to form an integral part of carbon accounting.

Nevertheless, the report does clearly illustrate the role many different habitats play in sequestering carbon, providing adaptation mechanisms to climate change and boosting biodiversity. It also illustrates how management, restoration and regeneration can maximise these benefits.

ANNEX 1: OVERVIEW OF DEFINITIONS OF NBS IN THE LITERATURE

Source	**Definition**
Cohen-Shacham *et al*. (2016).[3] [IUCN definition]	'actions to protect, sustainably manage and restore natural or modified ecosystems, that address societal challenges (e.g. climate change, food and water security or natural disasters) effectively and adaptively, simultaneously providing human well-being and biodiversity benefits'
European Commission (2015).[77] [EU definition]	'solutions that are inspired and supported by nature, which are cost effective, simultaneously provide environmental, social and economic benefits and help build resilience'
Nature-based solutions initiative.[78] [Oxford University]	'involve working with nature to address societal challenges, providing benefits for both human well-being and biodiversity. Specifically they are actions that involve the protection, restoration or management of natural and semi-natural ecosystems; the sustainable management of aquatic systems and working lands such as croplands or timberlands; or the creation of novel ecosystems in and around cities. They are actions that are underpinned biodiversity and are designed and implemented with the full engagement and consent of local communities and Indigenous Peoples.'
Kabisch *et al*. (2016).[79]	'is one of several concepts that promote the maintenance, enhancement, and restoration of biodiversity and ecosystems as a means to address multiple concerns simultaneously'
Maes and Jacob (2015).[80]	'any transition to a use of ecosystem services with decreased input of non-renewable natural capital and increased investment in renewable natural processes'
Van de Bosch and Sang (2017).[81]	'solutions to societal challenges that are inspired and supported by nature which are cost effective, provide simultaneous environmental, social and economic benefits, and help build resilience'
Frantzeskaki (2019).[82]	'living solutions underpinned by natural processes and structures that are designed to address various environmental challenges while simultaneously providing multiple benefits to economy, society and ecological systems.'

Albert *et al*. (2019).[83]	'(i) alleviate a well-defined societal challenge, (ii) utilize ecosystem processes of spatial, blue and green infrastructure networks, and (iii) are embedded within viable governance or business models for implementation'
Van der Jagt *et al*. (2017).[84]	'multifunctional 'green' interventions delivering upon the social, economic and environmental pillars of sustainable development'
United Nations World Water Assessment Programme (2018).[85]	'inspired and supported by nature and use, or mimic, natural processes to contribute towards the improved management of water. An NbS can involve conserving or rehabilitating natural ecosystems and/or the enhancement or creation of natural processes in modified or artificial ecosystems'
Zolch *et al*. (2017).[86]	'solutions using nature and ecosystem services to provide economic, social as well as environmental benefits and span from natural ecosystems to novel ecosystems that are either intentionally or unintentionally created by humans'
White *et al*., (2019).[1]	'when ecosystem services have contributed the large service input into an outcome that has created enough benefit to solve a well-defined problem' (with possible service types being ecosystem, technological and social).'

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SECTION 1: HABITAT SPECIFIC NATURE-BASED SOLUTIONS: A REVIEW OF THE AVAILABLE EVIDENCE

WOODLANDS

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1. KEY POINTS

1. The United Kingdom's forests currently store 1.09 billion tonnes of carbon and sequester about 4.6% of the country's total emissions. The UK government's commitment to plant over 30,000 extra hectares of woodland per year by 2025 offers significant opportunities to mitigate climate change through carbon sequestration, although the full benefits will not be felt before 2050. Depending on the choice of site, species and establishment method, these new woodlands could also benefit biodiversity and deliver multiple ecosystem services.
2. Large-scale afforestation should avoid peatlands, productive agricultural lands and habitats of high conservation value, focussing instead on poor-quality grazing land of which there is more than enough to fulfil government planting commitments. However, this loss of grasslands would reduce the UK's capacity to produce meat and dairy products (unless other regions were further intensified), which could do more harm than good unless we switch to more vegetable-based diets, if tropical forests were destroyed to create pastures which supply the UK with imported meat.
3. Small-scale establishment of native woodlands within agricultural landscapes would provide opportunities to reconnect fragments of ancient woodland, protect wildlife, and better connect people with nature if made accessible. Natural establishment of woodlands should be encouraged, where appropriate.
4. Non-native conifer plantations provide timber and other wood products, reducing the UK's international environmental footprint; conifer plantations can be damaging for nature, but careful planning can reduce that impact and even benefit some species. In order for plantations to meet their potential, adaptation of woodlands and forestry to future hazards is essential. This includes ensuring diversity is increased in plantations, pests and diseases are controlled, and creating complex canopy structure.
5. Selective harvesting of trees in native woodlands provides a source of fuelwood (i.e. a renewable energy that substitutes for fossil fuels) and other wood products. Some species thrive in selectively-logged woodlands, but felling large, old trees and clearing deadwood is harmful to birds, bats, lichens, invertebrates and fungi that are woodland specialists, so these should be avoided. They are also important carbon stores. The UK would require damaging levels of wood extraction to meet its energy demands through home-grown fuelwood.
6. Past grant schemes aiming to support woodland creation have rarely met annual planting targets due to social factors including bureaucracy, traditional perceptions of land management, and financial viability. Local, and regional participatory approaches are needed to negotiate around different objectives and build collective power for brokering public payments for nature-based solutions.

2. INTRODUCTION

The world's woodlands could play a significant part in offsetting greenhouse gas emission (GHGs) in the next 20 years, providing humanity with GHG removal capacity to offset emissions in hard-to-decarbonise sectors[1,2,3,4]. Woodlands already remove about 25% of anthropogenic carbon dioxide emissions from the atmosphere at a global scale[5,6]. If the international community halted deforestation, restored degraded forests and replaced lost woody cover, then woodlands could provide up to a quarter of the cost-effective climate mitigation required in the coming decade to stabilise warming to below 2 degrees Celsius[7]. The independent UK Committee on Climate Change (CCC) has recommended that tree cover is increased from 13% to at least 17%, existing woodlands are managed more effectively and agroforestry is encouraged[8]. The 25 Year Environment Plan also commits the UK to establish new woodlands[9]. Ambitious woodland policies are often met with varying opinions as to the best approach, and in England this is highlighted by responses to the English Tree Strategy consultation. Confor, which represents the views of forestry businesses, urges large-scale commercial planting, facilitated by a simplified planning process[10]. In contrast, two environmental charities call for woodland cover to be doubled[11,12], while others emphasise that new woodlands could help reconnect nature[13]. This variety of opinions reflects the fact that woodlands can provide nature-based solutions (NbS) to multiple societal needs - including timber production, carbon drawdown, and improved mental health by connecting people with nature - and that various institutions have different priorities, each with varying implications.

3. CLIMATE CHANGE MITIGATION POTENTIAL

The UK's woodlands store large quantities of carbon (1.09 billion tonnes of carbon (t.C)) and currently sequester about 4.6% of the country's GHGs each year[14,15]. This regulating service has been valued at £1.96 billion per year[16]. However, the forest carbon sink has steadily declined over the past 20 years[14]. There are broadly three ways to increase the UK's woodland carbon sink in future (Figure 1, based on[17]):

AFFORESTATION

Afforestation of farmland is effective at sequestering carbon in plant material, litter and soil. The UK is committed to planting 30,000 hectares (ha) of woodland per year by 2025, with each of the four countries having their own targets and support schemes. The CCC estimates that these new woodlands will sequester an additional 2 million tonnes of carbon dioxide per year (t.CO_2/yr) by 2030. Simulation models suggest that planting 23,200 ha of new woodland annually for the next 40 years would eventually sequester an extra 12 million t.CO_2/yr (cf. 19 million t.CO_2/yr at present) but it would take until 2070 to reach that peak (Figure 1). An alternative to planting trees is to allow natural afforestation[18]. Diverse naturally established forests can accumulate carbon rapidly once sufficient trees have colonised a site[19]. However, the initial phase of woodland establishment is hit-and-miss, depending on the proximity of seed sources, the density of ground vegetation, and herbivory pressure[20], potentially delaying carbon drawdown by a decade or more[21]. Unless these issues are resolved (e.g. by assisting seed dispersal[18], scarifying soil[22], planting clusters of key trees[22], and controlling herbivores[20]), natural colonisation remains a risky approach to meet 2050 emissions targets.

PROTECTING EXISTING FORESTS

Protecting natural forests from being logged ("proforestation") is recognised internationally as an effective NbS for removing CO_2 from the atmosphere[3,23,24,25]. Previously logged woodlands become major carbon sinks once protected and allowed to regenerate, and even after maturity can continue to accumulate carbon in dead wood and soils[26]. However, historical deforestation has left the UK as one of Europe's least wooded countries[17,27] and, while it is important to protect our remaining native woodlands, more trees need to be established to create a significant carbon sink (Figure 1). Increasing rotation lengths of commercial plantations also leads to carbon sequestration[28], but is not sufficient to meet emissions targets (Figure 1). However, there is also uncertainty about the permanence of woodland carbon stores (both native and exotic conifers), given risks of introduced pest and disease[29].

INCREASED PRODUCTION OF TIMBER AND OTHER WOOD PRODUCTS

The 6.5 million tonnes of wood that is harvested from UK woodlands annually meets only a small fraction of domestic demand[8]. The CCC has recommended that more native woodlands are brought into sustainable management to meet this demand[30]. For instance, harvesting trees to produce fuelwood reduces carbon stocks in the woodlands themselves, but the fuelwood substitutes for fossil fuel so reduce emissions overall. A similar principle applies with timber production in commercial plantation: making more buildings from wood could significantly reduce emissions from the construction sector, as concrete production is a major emitter of CO_2[31], so, maximising wood production can be beneficial for climate even if it comes at the expense of carbon storage in the plantations. Calculating the abatement potential of managed woodlands requires complex carbon accounting that transcends industrial sectors and tracks the persistence of harvested products through time, but these accounts are seldom available[32]. The simulation model indicates an additional 30% carbon sink once harvested wood is included (Figure 1).

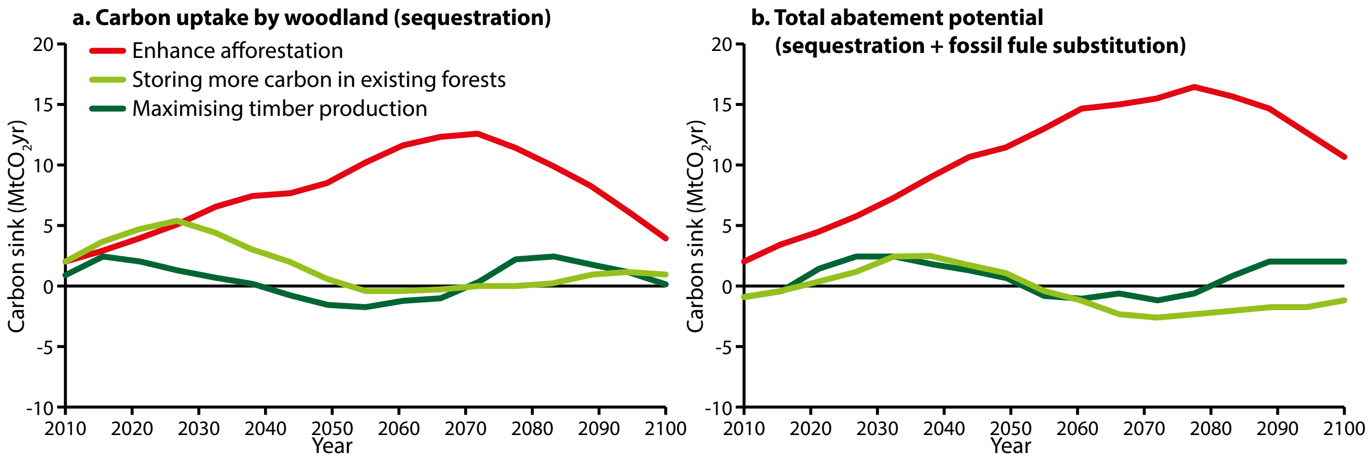

Figure 1. Predicted impacts of different management interventions on the UK woodland carbon sink (adapted from the Read report of 2009[17]). The simulation models predicted the additional carbon sink resulting from the management interventions, compared with "business as usual". Three scenarios are presented: enhanced afforestation equating to 23,200 ha of new woodlands each year from 2010 to 2050 (red); reduced harvesting of forests to increase their carbon stocks (light green); and optimising rotations to maximise wood production (dark green). Note that simulations did not include the carbon sink that could arise from protecting naturally established woodlands from deer. Panel (a) gives the woodland sink (i.e. carbon stored in trees, soil and litter) while (b) gives total abatement - the woodland sink plus the carbon stored in harvested wood or consumed in place of fossil fuel. For comparison, the CCC estimates that an additional carbon sink of 17 million t.CO2/yr would be generated by 2050 if its recommendations are adopted.

The mitigation potential of UK forests is affected by three poorly quantified phenomena. First, conifer plantations absorb more solar radiation than deciduous broadleaf forests, and thereby warm the atmosphere[33]. The large-scale transformation of Europe's broadleaved forests to conifer plantations over the past three centuries has contributed to global warming, largely counteracting the climate benefits of locking additional carbon in forest biomass and soils[34,35]. Secondly, tree planting can reduce soil carbon stocks. About 70% of forest carbon is held in the soil[36], and site preparation typically releases carbon from stores[37], creating an initial "carbon debt" which needs to be repaid before management delivers any climate benefit[38,39]. Trees also alter the quality of soil organic matter as they grow[40] with long-term consequences for carbon storage[41]. Thirdly, the removal of carbon from forest ecosystems via stream-water transport[42,43] is poorly quantified. We recommend further research into these factors to refine predictions of carbon drawdown associated with woodland establishment and management.

4. CLIMATE CHANGE ADAPTATION POTENTIAL

Woodlands can provide climatic adaptation benefits for people, such as flood and erosion alleviation[44] (see *Chapter 6: Freshwater Systems* for analysis of tree planting impacts on flooding), but in order to do this, adaptive measures are needed to create forests and woodlands that will be resilient to future risks to continue providing NbS to society[29,45,46]. Climate change may threaten woodlands by increasing the frequency of disturbance events that kill trees[47]. Unlike other sectors, adaptive measures for forestry need to account for long time lags between tree establishment and maturity.

Three adaptations are key:

a. **Increase diversity (genetic and species):** Species-rich ecosystems are typically more resilient to environmental threats because different species respond differently to stressors, thereby buffering the system as a whole[48]. Native tree species are genetically diverse and thus have likely to enable adaptation and resilience to climate change; natural regeneration or locally sourced seed should continue to be a core component of future woodland creation when biodiversity conservation is a key objective[49]. The Forestry Commission recommends including species and provenances with more southerly origins[29,45,46].

b. **Control pests and diseases:** Significant barriers to forest adaptation include widespread tree mortality from pests and diseases, with risks increasing due to reliance on imported plants[29]. The UK Plant Health Risk Register currently includes approximately 300 pest and disease species likely to attack trees and pose a greater immediate risk to woodlands than climate change. Resistance strategies, such as integrated pest management practices, raising more planting stock in the UK, using natural establishment where possible, improving biosecurity to prevent the movement of contaminated water and soil, and increasing surveillance to catch outbreaks early, will reduce their likelihood and frequency. Engagement of the plant supply chain in the new Plant Health Management Standard and associated Certification Scheme will be an important mechanism to achieve this.

c. **Improve structure:** New woodlands, whether forestry plantations or new native woodland can be established with future diverse canopy and forest structure planned from the outset, to increase resilience to hazards[50]. For example, planting in some areas can be delayed, fast-growing species can be planted in mixtures with slower-growing species, and wider spacings can be used to allow some natural vegetation to establish or thinning regimes can be planned to ensure structural diversity develops with stand age and size[51]. It is harder to transform existing forests into continuous cover systems, but work is being done to develop successful techniques[52].

5. BIODIVERSITY VALUE

BRINGING NATIVE WOODLANDS BACK INTO ACTIVE MANAGEMENT

The CCC recommends selective harvesting of what they consider to be "neglected" native woodlands to produce fuelwood and other wood products. Limited harvesting of overgrown woodlands creates structurally diverse canopies that favour ground-layer plant and tree regeneration[53,54,55]. However, old trees and deadwood should be retained in managed woodlands, as they are immensely valuable for woodland specialist species[53,54,55] and are nationally uncommon[56]. Ancient woodlands are particularly valuable sites for veteran trees, deadwood and woodland specialists but occupy just 2.2% of the UK[57]. Harvesting any veteran trees should be avoided as it takes many decades to accumulate woodland specialists in secondary woodlands[58,59,60]. Other forms of sustainable management that can deliver benefits for nature include: harvesting non-native conifers that were planted in 39% of ancient woodland sites in the twentieth century, creating opportunities for nature to recolonise; reducing or eliminating populations of deer and uncontrolled livestock which browse on seedlings and prevent regeneration from occurring, recognising that UK woodlands lack the predators that would have once kept these herbivores in check; clearing of invasive species, including *Rhododendron ponticum*, to enable natural regeneration processes to resume, and ground flora and epiphytes to re-cover[53,54,55].

INCREASING THE COVER OF NATIVE WOODLANDS

New woodland planting provides opportunities to create "more, bigger, better and joined" nature reserves[61]. In particular, there are opportunities to increase the resilience of the UK's network of 42,000 ancient woodlands (at least 250 years in Scotland or 400 years in other UK nations), which are predominantly less than five hectares in size and highly fragmented[53,55,62]. Natural or assisted establishment is most appropriate when expanding native woodland for biodiversity conservation, as it produces a more diverse structure, with better matching of species to soil and topography, provided relevant species have seed sources in the area. Culling of deer in areas of the Scottish Highlands has led to the gradual return of pine and birch woodlands[20] and several "rewilding" projects have led to the return of open woody habitats once grazing pressure from domestic livestock is reduced, and, sometimes, wild pigs re-introduced to disturb the soil[63]. Rewilding projects that return woody cover to agricultural landscapes have had some notable successes at restoring rare wildlife[63]. Planting native woodlands on species-poor farmland increases local biodiversity over time[49,53,54,64] and improves the connectivity of fragments[60]. Woodlands imperil wildlife if allowed to establish on open habitats of high conservation value ("priority habitats"), such as lowland heathlands and species-rich grasslands[65], so these should be avoided. Local populations of native species are genetically diverse and locally sourced seed should usually be a core component of future tree planting when biodiversity conservation is a key objective[49], although there may be opportunities to diversify impoverished floras and expand the range of rare species by introducing species from further afield.

Photo 1: Natural establishment adjacent to remnant Caledonian Pine forest in a deer exclosure in Glen Affric, Scotland © Emily Warner

INCREASING THE COVER OF FORESTRY PLANTATIONS

Forestry plantations negatively impact biodiversity if planted into species-rich habitats[66,67,68]. However, when planted into degraded agricultural land, they can benefit some organisms[69,70]. Spatial planning can reduce negative impacts[71]. For instance, protecting native woodland and herbaceous habitats near stream courses and retaining patches of old trees within the landscape can enhance opportunities for nature without compromising productivity and is a requirement under the UK Forestry Standard.

6. TRADE-OFFS

WHERE TO PLANT TREES

Afforesting high-quality arable land (i.e., Grade 1, 2 and 3a agricultural land) should be avoided, as it reduces the UK's capacity to produce food, leading to an even greater reliance on food imports which are linked to deforestation in the tropics, releasing CO_2 from those forests and destroying biodiversity hotspots[72]. Additionally, planting trees on productive land presents a major opportunity cost[73]. However, there may be opportunities to establish groves of trees on steep, inaccessible or unproductive pockets within arable landscapes, and also in agroforestry, hedgerows, field margins and stream sides, without compromising food production[74]. (see *Chapter 5: Arable Systems* for detailed discussion). Peri-urban woodlands also provide natural places for people to enjoy nature, and have a social value that outweighs any loss of arable land[73].

Establishing woodlands on low-biodiversity grasslands (Grades 3b or 4 agricultural land) offers the best prospect for large-scale afforestation. The Forestry Commission has identified five million ha of "low risk" land[30], while the Friends of the Earth's figure is 1.4 million ha, having screened out species-rich grassland and priority habitat for conservation[11]. Even if further areas of priority habitats are discovered[65], there appears to be enough "rough grazing land" to double woodland cover. However, afforestation of these grasslands will not deliver climate benefits unless it is accompanied by a shift in diet away from meat and dairy products and/or greater productivity on the remaining land[11]. This shift is necessary because without it, we would need to import additional meat and dairy products from overseas, with knock-on consequences for land use change in other regions of the world (i.e., telecoupling[75]).

Afforestation of peatlands and organic-rich soils should be avoided. Afforestation requires improved drainage to achieve strong tree growth[76], but aeration accelerates microbial decomposition of the peat, releasing CO_2 and generating a major initial carbon "debt" that takes years to repay through tree growth[77]. Planting on peat that is deeper than 50 cm is now outlawed under the UK Forestry Standard, but planting on shallow peat continues, supported by evidence that these plantations can sequester carbon over the production cycle if the productivity is high enough. However, modelling suggests that peats should be avoided altogether to avoid damaging the soil, and that new plantations should be created in low-grade agricultural land instead[78]. In one study, native birches and pines planted on organic soils were found to result in carbon loss from the soil which offsets carbon accumulation within living biomass, leaving no climate benefit of afforestation after 12 and 39 years[41]. Policies regarding the establishment of woodlands on carbon-rich soils (including moorlands and heathlands) may need refinement if further evidence emerges of adverse effects on the large stocks of carbon held belowground.

WHICH SPECIES TO PLANT

Successive governments have subsidised afforestation with non-native conifers, recognising that Sitka spruce and a handful of other conifers can deliver much greater volumes of merchantable timber than native woodlands[71,79]. This has created a rural industry that employs 43,000 people in forest management and primary wood processing, providing timber and other wood products to a country heavily reliant on imports. However, several native broadleaf species store more carbon than introduced conifers across the drier and warmer parts of the UK[19,28] [Morecroft, pers. comm.]; mixed-species planting that leads to oaks dominance through succession also results in more durable carbon stores than achievable by conifer plantations[80]. There is currently little incentive for landowners to plant broadleaf woodlands, because carbon storage remains a public good, but the value of this service far exceeds the market value of timber[16], and if that were reflected in government incentive schemes, then more broadleaf woodlands might be planted. The UK Forestry Standard provides a framework for more sustainable forestry, discouraging geometric plantings of single species in large even-aged blocks in favour of mixed systems including native species (at least five per cent)[81]. Broadleaved woodlands store about 29% of the carbon in UK forest biomass and could sequester significantly more if established over sufficient scales[28]. Based on studies in Europe[82,83,84], mixed-species forests sequester carbon more rapidly than monocultures[85] and are more climate resilient[48], particularly in regions where climate imposes a strong limitation on wood production[86]. We argue that any government subsidies intended for biodiversity conservation should be directed to native woodland creation and management, under the public money for public good principle.

RENEWABLE ENERGY VS. FOREST CARBON

Wood can be used to heat buildings and fuel electrical turbines, offering a substitute for fossil fuels[87]. The UK would require afforestation on an unrealisable scale to meet the demands of its existing wood-powered stations domestically, let alone expand power production and large-scale afforestation with non-native species for energy production would be environmentally damaging or compete for land with food production[88,89]. However, small-scale use of wood can potentially be environmentally sustainable, particularly if using thinnings and other waste products from forestry, native woodland and hedgerow management[87], and might be considered as NbS in some limited circumstances.

PAYING TO PROTECT TROPICAL FORESTS VS. AFFORESTATION

Protecting natural tropical forests could deliver immediate climate benefits at a fraction of the cost of other climate mitigation activities[90], and benefit some of the billion people who rely on forests for their livelihoods[88], if governance and social justice issues can be resolved[89]. However, international commitments to create new plantations in developing countries risk harming natural ecosystems and livelihood, without delivering climate benefits, if hastily implemented without due diligence[23].

7. HUMAN WELLBEING VALUE

Woodlands provide multiple services in addition to climate and biodiversity benefits, including timber and fibre production, water quality and green space for human wellbeing[91]. Natural capital accounts show that the non-market benefits of woodlands are about 12 times more valuable than the market benefits of wood production[16]. This calculation does not place a monetary value on biodiversity, but biodiversity underpins most natural capital elements.

CASE STUDY 1

Thetford Forest is a large commercial forest on the Norfolk/Suffolk border mostly planted with conifers between the 1920s and 1960s in an area of low-productivity sandy soil supporting arable fields, grasslands and heathlands. An analysis of a wide range of management options and ecosystem services has clarified the nuances between the trade-offs and synergies associated with different management techniques[92]. This led to recommendations for a landscape design that balances and maximises overall ecosystem service delivery, including some restoration of ecologically important heathland, rather than focus on a single benefit such as timber production[93].

Photo 2: Heathland in Thetford forest
© Nick Macneill (cc-by-sa/2.0)

8. IMPLEMENTATION OF WOODLAND NBS

The prevailing political and policy context in the UK provides scope to turn the potential for NbS into practical action. With a focus on 'public money for public goods' and the need to replace the Common Agricultural Policy (CAP)[94], there are new opportunities to develop market-based approaches to catalyse change, recognising that woodland planting and ongoing management activities need to be commercially attractive.

There would be strong financial incentives to buffer ancient woodlands and 'integrate' large scale woodland projects into suitable upland landscapes if the social cost of the interlinked climate and biodiversity crises was reflected in the subsidies governments were willing to pay landowners for establishing and managing woodlands. This would have to be carried out as part of a managed transition away from existing farming practices. The total social value of carbon sequestered by UK woodland has been valued at £239/ha/yr, which is greater than the expected returns from timber production[27]. Incentives to establish woodlands for carbon sequestration are currently too small to drive change on the scale required: only 266 projects have registered for the Woodland Carbon Code – a voluntary standard by which verified carbon credit can be produced - since 2011, and these are predicted to sequester about 6.2 million t.CO_2 *in total* over their 100-years lifetime[95]. This is relatively small given that the UK's emissions are currently 351 million t.CO_2 *per year*[15]. The government-backed Woodland Carbon Guarantee makes steps towards addressing this issue, offering landowners the chance to bid for guaranteed carbon payments to make tree planting a financially viable option.

It is widely recognised that research, policy, and practice must pay more attention to socio-ecological considerations to reconcile different objectives[96] which must be taken into consideration when planning woodland NbS. Past grant schemes aiming to support woodland creation have rarely met annual planting targets due to social factors including bureaucracy and traditional perceptions of land management, and because they have struggled to compete financially with other options. Research, as well as emerging partnerships in practice, support the development of local, landscape-scale, or regional participatory approaches. These partnerships enable negotiation around different objectives, collaboration across land ownership boundaries, and build collective power for brokering public payments for NbS, marketing of local products, and maintaining long-term monitoring. There is a need to support locally led partnerships which can identify the NbS of importance to their region, and how these should be delivered[97]. Woods and forests can deliver considerable ecosystem services, including carbon sequestration, if carefully thought through, located and implemented.

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HEATHLANDS

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1. KEY POINTS

1. Heathlands are successional habitats that store high levels of carbon, mainly in the soil.
2. Most types of heathlands require regular management to maintain their structure, function and characteristic assemblage of species which can conflict with climate mitigation initiatives (e.g. planting trees or allowing natural succession).
3. Any active climate mitigation initiatives need to consider the resulting changes in biodiversity, including losses of heathland specialists and other open ground species.
4. Soil disturbance as a result of management actions can increase carbon emissions from the soil stock, thus soil conservation and minimal disturbance is the best mitigation tool against carbon emissions from the ecosystem.
5. Heathlands undergoing shrub or tree encroachment may release carbon into the atmosphere from the soil, which will not be offset by the growing shrubs or trees for decades.
6. Removing conifers from afforested heathland may result in some carbon emissions but will benefit the soil carbon stores and heathland biodiversity in the long term.
7. Creating heathland from ex-arable land will result in increased carbon sequestration in soils and vegetation.
8. Some grazing can have a positive effect on habitat quality, but it can increase greenhouse gas emissions depending on the species and breeds.
9. Restoring degraded heathland (e.g. overgrazed and transformed into grassland), will also result in increased carbon sequestration in soils and vegetation.
10. In the uplands a reduction in grazing levels on heathlands and more careful targeting of habitats suitable for burning would result in increased carbon sequestration.

2. INTRODUCTION

In the United Kingdom heathlands characterised by heathers (shrubs of the Ericaceae family) are found in the lowlands and uplands. They may also contain bare ground, grassy patches, bryophytes and lichens and generally have a limited cover of trees and bracken[1,2]. Heather-dominated vegetation on deep peat, in coastal situations or on mountain tops, including blanket bog, alpine heath and moss heath[3], are beyond the scope of this chapter. Further information on the potential for nature-based solutions (NbS) in peatlands can be found in *Chapter 3*.

Heathlands occur in mostly acidic and nutrient-poor soils and show transitions from dry to wet types on a variety of substrates from mineral soils to shallow peat[1].

In the UK, although ecologically they are a continuum, there is a management-based division between upland and lowland heathlands and these face different threats respectively, for example, under-management in the lowlands and livestock overgrazing and overburning in the uplands[10].

Although the post-glacial wildwood would have had heathy areas, heathlands expanded and were exploited by people over centuries[4,5]. The area covered by heathland in the UK has declined significantly, particularly since 1945; the areas that remain have suffered declines in habitat quality and species losses[6]. Despite the need for regular management to maintain the characteristic openness of this habitat, people often see them as natural or even wild places, particularly in the uplands.

Figure 1: (Left) Lowland Heathland (Dersingham Bog NNR, Norfolk ©Isabel Alonso, NE); (right) Upland heathland (Stanage Edge, Derbyshire ©David Glaves, NE)

3. CLIMATE CHANGE MITIGATION POTENTIAL

Most of the carbon in heathland ecosystems is in the soil (ONS 2020[7]: 98% in soils versus 2% in vegetation). Organic soils (soils with greater than 60% organic matter[8]) contain the largest amount of carbon[9,10] but mineral soils can also be as important carbon stores[11,12]. Thus, soil conservation and minimal disturbance is the best mitigation tool against carbon emissions from the ecosystem.

The main studies looking at soil carbon content in the UK group together "moor and heath"[13,9]. These studies include a variety of soil types with a wide range of carbon content, likely including degraded blanket bog with a high cover of heathers which falls outside the definition of "heathlands".

[1] Sites with deep peat (at least 0.3 m in England or over 0.5 m in Scotland), are considered blanket bog, even if the aboveground vegetation is dominated by heathers[58]. Blanket bog will be considered in the *Chapter 3*.

However, the values for carbon stocks in heathland soil from the literature that we do have are similar and range from 82 to 103 tonnes of carbon per hectare (t.C/ha)[13,7]. Figures for carbon content of the heathland vegetation component are more variable (from 0.5 to 49 t.C/ha), probably reflecting the varied conditions of the experimental sites. The higher figure is for an uncommon situation: an upland site fenced and unmanaged for 25 years[14]. As a result, it is currently difficult to extrapolate the impact of management on the carbon stores of particular soils. Further studies comparing mineral and organic soils, across a range of geographical locations, in the uplands and lowlands, would fill a significant evidence gap.

MANAGEMENT IMPACTS AND CARBON SEQUESTRATION

3.1 TREE AND SCRUB MANAGEMENT ON HEATHLANDS

Evidence indicates that trees growing on heathlands do not necessarily lead to significant gains in carbon stocks[27,34]. One study indicated that natural afforestation in the uplands only resulted in an additional 3 tonnes of carbon dioxide per hectare per year (t.CO_2/ha/yr) [34](Figure 2). Further, research demonstrated that planting trees in upland heath reduced carbon sequestration and increased emissions due to changes in the soil and biodiversity losses[15,16]. Tree planting in East Anglian heaths also reduced soil carbon by approximately 0.6 t.CO_2/ha/yr in 21 years[14] (Figure 2).

Trees growing on wetter heathland soils, either planted or regenerating naturally, can increase carbon emissions from the soils, not compensated by the increase in the carbon stored in wood[17]. A study has shown that that planting trees on 2000 ha of coastal heath in Norway could result in 1.5 t.CO_2 sequestered in 50 years, but these heaths already have 0.9 t.CO_2 in the soil now and, for comparison, the Norwegian national emissions just from oil extraction are 51.3-55.0 t.CO_2 [18]. Therefore, on balance trees will only sequester a proportionally small amount of carbon but would damage the biodiversity of an existing habitat with important carbon stores in the soil. Further research also indicates that the carbon storage of open habitats (grasslands, heathlands and wetlands) has traditionally been underestimated and tree planting may not render the carbon sequestration results expected[19]. See *Chapter 1: Woodlands* for further discussion.

Reconnecting heathland patches by removing conifer plantations can result in carbon emissions[20], as does removing scrub and trees from neglected heathlands[20,34] but both interventions benefit heathland specialist species[21]. Furthermore, halting the natural growth of trees on most heathlands to maintain or enhance condition and cater for species characteristic of open heathland involves grazing, removing vegetation regularly and/or creating bare ground, which involves trade-offs with carbon fluxes.

In summary, there may be trade-offs between achieving the conservation objectives for heathlands and their characteristic species, and achieving climate mitigation objectives through afforestation[34]. Soil disturbance as a result of management actions can increase carbon emissions from the soil stock and should be minimised. The widespread natural growth of trees and scrub on heathlands should be controlled to help retain existing heathland soil carbon stocks and cater for heathland species characteristic of open and diverse vegetation structure. Open habitats, including grasslands and heathlands, particularly those in a degraded state, will be lost if tree planting is not carefully planned[22]. This highlights the need to conduct detailed environmental assessments at sites ahead of implementing potential NbS in order to minimise the risk of adverse outcomes.

3.2 RESTORATION FROM GRASSLAND

Heathlands that have changed into poor-quality grasslands as a result of increases in nutrient availability or inappropriate management[23,24] should be restored as they can store more carbon with an ericaceous cover[25,26,27].

Restoring upland heathlands can be achieved by adjusting grazing pressure, reducing inappropriate burning and clearing bracken[28]. Lowland heathland restoration, from degraded grassland or former agricultural grasslands, can include methods such as topsoil removal to reduce nutrient loads or chemically amending the soil to reduce the pH (for example through the addition of sulphur) to help establish ericaceous cover[29]. However, there may be unintended consequences after these drastic interventions, such as soil or archaeological damage[30] or increased availability of toxic elements such as aluminium[31] or impacts on invertebrates[32], which needs a site-specific restoration plan. Adding seeds[33] or plant plugs to the soil can sometimes be necessary too.

For example, one study[25] found that degraded upland heathland that changed into grassland had slightly larger vegetation carbon stocks (1.8 t.C/ha more) but much smaller soil carbon stocks (13.8 t.C/ha less) than the target heathland habitat (12 and 102 t.C/ha respectively) so overall, the system had lost carbon by being in poor condition. On the other hand, restored heathland had similar vegetation carbon content to the target heathland (only 0.1 t.C/ha less) and the soil carbon stock was only slightly smaller (1.9 t.C/ha less).

Overall, where heathlands are degraded and change into grasslands, their soil carbon stocks are significantly lower than good quality heathland habitats. Therefore, where possible, management practises should aim to restore heathlands to their target heathland habitat condition to improve carbon stocks.

2.3 BURNING

Burning has been traditionally used to manage heathland vegetation but heathlands change from carbon sinks to sources when burned due to reduced photosynthesis[34,35] and increased emissions, especially if the fire takes place in summer (Figure 2). However, it is possible that controlled fires on upland heathland that do not damage the organic soil layer and do not have an underlying peat layer could be carbon neutral[36], though this depends on burn intensity, severity and rotation length[37]. Longer burning cycles, smaller proportions burnt annually, avoiding peat soils (for further information, see *Chapter 3: Peatlands*) and burning under appropriate burning conditions based on good practice can help to reduce carbon emissions from burning heaths[38,39,40]. Less frequent burning and on smaller areas can also help improve the habitat condition, by producing a more diverse vegetation structure[2].

Careful controlled burning of heathland can be carried out to achieve biodiversity objectives, but needs to follow good practice (Heather and Grass Burning and Muirburn Codes).

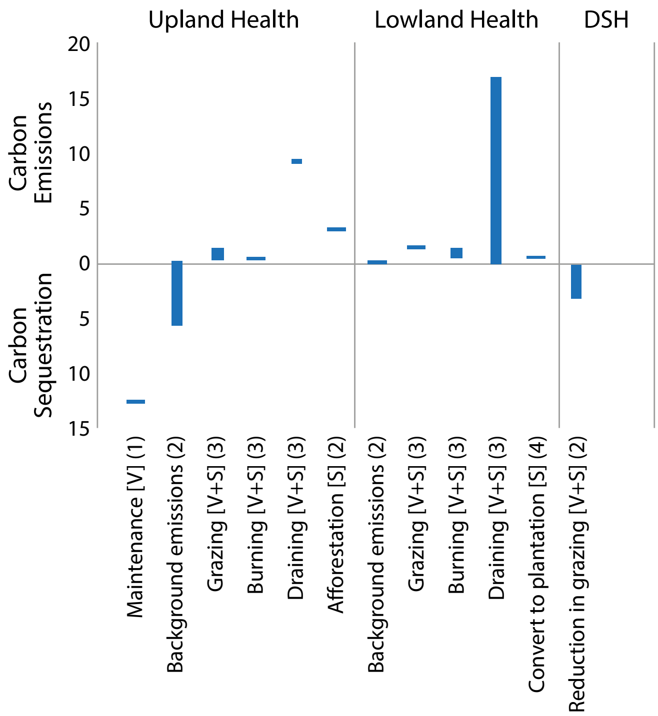

Figure 2: Summary of the impacts of typical heathland interventions on **C fluxes (t.CO_2/ha/yr)**. After [(1)]Quin et al. (2015), [(2)]Sozanska-Stanton et al. (2016), [(3)]Carey et al. (2016), [(4)]Morison et al (2012). V= vegetation; S= soil; DSH= Dwarf Shrub Heath (general data for both upland and lowland, or unspecified). Maintenance here means light grazing by livestock and deer, no burning[26]. Background emissions (e.g. through bacterial oxidation) were calculated from field studies following IPCC methods for sites across Wales and Scotland[34].

4. CLIMATE CHANGE ADAPTATION POTENTIAL

Both lowland and upland heathlands have been described as having a "Medium" sensitivity to climate change[41]. Heathlands are sensitive to changes in hydrology and the potential increase in the extent and frequency of fires due to projected higher temperatures and more frequent severe droughts. Also, heather beetle outbreaks could potentially increase in numbers in response to warmer winters[42]. These factors coupled with increased nutrient availability (e.g. through atmospheric nitrogen deposition from fossil fuel burning and intensive farming) could result in unpredicted and unwanted changes in the vegetation composition and structure (e.g. increased biomass[43,44]) which could affect the current biodiversity of the habitat. Increased nitrogen deposition does however lead to increased carbon sequestration in the litter and organic horizons until a point of saturation[44] and managing the heather to maintain it at a young growth stage (building phase) maximises carbon sequestration[44].

Both upland and lowland heathlands are likely to suffer a deterioration in condition and change into other habitat types as a result of changes in climate. In the lowlands, this is likely to involve a change from lowland heathland to acid grassland. Meanwhile, upland heath vegetation is expected to become more similar to that of lowland heath[39].

Drought can result in increased CO_2 emissions in wet heaths: carbon in soils decreased 60% with experimentally induced drought in just two months[45,39].

Enabling heaths to adapt to climate change will be necessary to enable them to continue to act as a NbS. Reducing other pressures such as recreational disturbance and atmospheric nitrogen deposition and continuing appropriate management may help heathland sites adapt to climate change[41]. Tree cover, particularly native broadleaves (e.g. birch or pedunculate oak) and in Scotland, native Caledonian pine, could be allowed to grow in some areas, particularly ecotones, to provide some heterogeneity in the landscape. However, to reduce the loss of heathland species and maintain favourable condition, tree cover should be kept below 15% in lowland heathlands[1] and below 20% (scattered native trees and scrub) in upland heathlands[2].

In a changing climate, appropriate management of heathlands can help to: conserve soil, especially organic soil which accumulates carbon; reduce the impact of flooding and wildfires; increase biodiversity, especially of characteristic heathland species (e.g. solitary bees and wasps); and provide connections with nature which can be enjoyed by all[1,2,40,46].

5. BIODIVERSITY VALUE

Historically, heathlands have been home to a wide range of species. Today in England alone, lowland heathlands are home to 133 priority species and upland heathland to 35, most of which require bare ground and short vegetation (Figure 3), which can only be provided by active management[21]. Conversely, less than a third of these species require scrub or wood-edge. Therefore, neglect or afforestation would benefit very few heathland species and would be detrimental to the majority.

It has been suggested that "dynamic scrub" (i.e. scrub developing in some areas for a few years before being controlled), in particular including birch, willow, gorse and hawthorn, without becoming dominant or developing into large blocks should be encouraged[21].

Large-scale habitat mosaics could potentially support more priority species[47] although some priority species require very specific conditions or management (e.g. heavy grazing and soil disturbance and/or ungrazed nectar sources and/or scrub). On the other hand, reductions in intensity of management, especially grazing, and mixed grazing with cattle or ponies can contribute to restoration and reduce fragmentation of upland heathland and associated large-scale habitat mosaics[48] (see Case Study 1 below) to the benefit of some scarce and declining upland species[49,50].

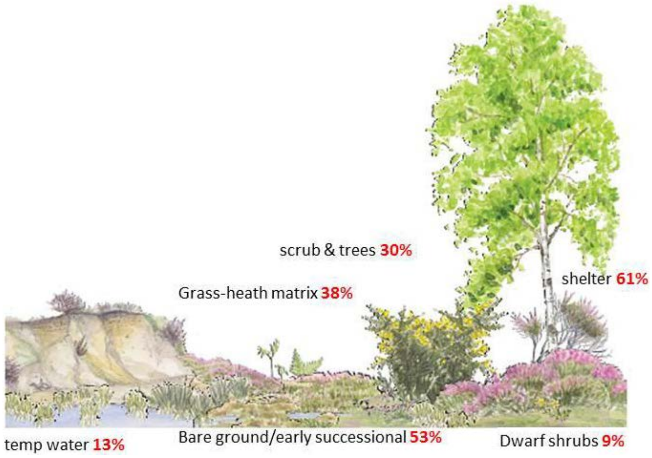

Figure 3: Percentage of UK priority species that occupy particular niches/habitats in lowland heathlands[21] © Isabel Alonso.

6. TRADE-OFFS

There may be a temptation to try and address the climate emergency by proposing potentially quick fixes, such as planting trees extensively, or allowing natural succession towards woodland, including on heathlands. However, as shown above, open habitats are important for specialised biodiversity and, in the case of heathlands, important carbon stores. As mentioned previously, tree planting without due environmental assessments, as happened last century and still happens today, can not only damage or destroy valuable wildlife habitats on heathlands, but also result in the opposite of the intended outcome: carbon emissions when planting on organic, wet soils. Carbon sequestration in wood may take years to compensate for these emissions[34].

No single land use management practice will result in significant carbon sequestration on heathlands, but various management approaches have other considerable benefits, for example positive impacts on heathland biodiversity[51] or maintaining soil carbon stocks[52]. Research by Thomas *et al.* (2013) has found that "strategies focussed solely on protecting carbon stores were largely inadequate for protecting biodiversity, but when carbon and biodiversity value were given joint priorities, up to 90% of both could be protected"[53].

7. ASSESSMENT OF THE QUALITY OF THE EVIDENCE

There has been some research in the last two decades on the impact of management on the carbon fluxes of dwarf shrub heath habitats. However, the information available is still limited. Studies show a large range of results, a reflection of the heterogeneity of the habitat as a result of climate, geography, history, management and conservation status.

Although the above information can be used to assess the likely impact of management interventions in terms of carbon emissions or sequestration, it is difficult to apply directly to specific sites. More studies are needed covering the range of the geographical distribution of heathlands, particularly more experimental studies looking at vegetation on different soil types.

8. CONCLUSION

In summary, NbS in heathland habitats should primarily aim to retain as much carbon *in situ* as possible, and at the same time benefit the heathlands' biodiversity. This should include appropriate heathland management that:

- Control the widespread natural growth of trees and scrub on heathlands to help retain the existing heathland soil carbon stocks and cater for heathland species characteristic of open and diverse vegetation structure. Any removal of trees must be conducted in a way that least disturbs the soils to preserve soil carbon stocks.
- Restore heathlands that have changed into poor-quality grasslands to target heathland habitat condition to help sequester more carbon and enhance heathland biodiversity.
- Strictly follow good practice (e.g. Heather and Grass Burning and Muirburn Codes) with regards to burning of heathland and avoids burning that could damage organic soil layers beneath vegetation.

Simultaneously, NbS can also facilitate the adaptation of heathlands to future climate scenarios. To capitalise on this, alongside the recommended management practices above, management of heathlands should also include:

- Blocking artificial drainage present to increase water retention in heathlands and avoid wet heaths drying out and releasing more carbon[35]. This has the added public benefit of reducing the risk of flooding downstream.
- Increasing the area, and especially width, of firebreaks to reduce the risk of catastrophic wildfires under drought conditions. On sandy soils, these bare and sparsely-vegetated open areas will also provide valuable habitat for many invertebrates[21] and notable vertebrate species such as sand lizards[54]
- Promoting the use by wild or semi-wild herbivores in heathland areas to prevent woodland encroachment and biomass accumulation.

Overall, heathland habitats are important for specialised biodiversity and, act as important carbon stores with the potential to facilitate adaptation to climate change. Therefore, heathlands should be managed in order to maximise these co-benefits and to function effectively as a NbS.

CASE STUDY 1: UPLAND HEATH RESTORATION UNDER AGRI-ENVIRONMENT AGREEMENTS AT WINSFORD ALLOTMENT, EXMOOR

The site is a moorland allotment covering 108 ha in South Exmoor Site of Special Scientific Interest (SSSI). Prior to 1993, it was the subject of an overgrazing investigation due to year-round sheep grazing and out-wintered cattle. This resulted in high mean stocking rates (SR) (0.33 Livestock Units (LU)/ha in summer and 0.68 LU/ha in winter) and a short 'grass-moor' sward (Photo 1).

Photo 1: Aerial photograph of 'grass-moor'-dominated Winsford Allotment, June 1992 (ADAS, © Crown copyright[55]).

It entered an Environmentally Sensitive Area (ESA) agreement in 1993 under a moorland restoration tier. Grazing was reduced to summer only sheep (0.10 LU/ha) with none in winter. In 2010, it entered a Higher Level Stewardship agreement with a revised summer only mixed sheep and cattle SR range of 0.09–0.15 LU/ha. The restorable heath area was restricted to *c.*45 ha on the plateau, with acid grassland, bracken and scrub grading to woodland on the slopes. The ESA agreement resulted in restoration of the plateau to heather-dominated dry and wet heath over ten years[55] (Photo 2) with recovery continuing in 2014[56].

Photo 2: Restored heath on Winsford Allotment plateau, September 2003 (© David Glaves).

This was reflected in a rapid decline in the mean percentage of grazed heather shoots (88% in 1993 to 10% in 1996) and a more gradual overall increase in heather cover (overall cover from 5% in 1993 to 35% in 2014 and from 10% to 60% in quadrats with heather present, Figure 4). Mean dwarf-shrub height also increased from 5 cm in 1993 to 23 cm by 2003 and 48 cm by 2014. There were also corresponding increases in bracken and scrub on the slopes, and in breeding skylark and linnet numbers. The heath met all dry heath condition assessment targets in 2014 (in ≥90 of samples), apart from for number of indicator species, probably attributable to slow recovery from the historically high grazing levels.

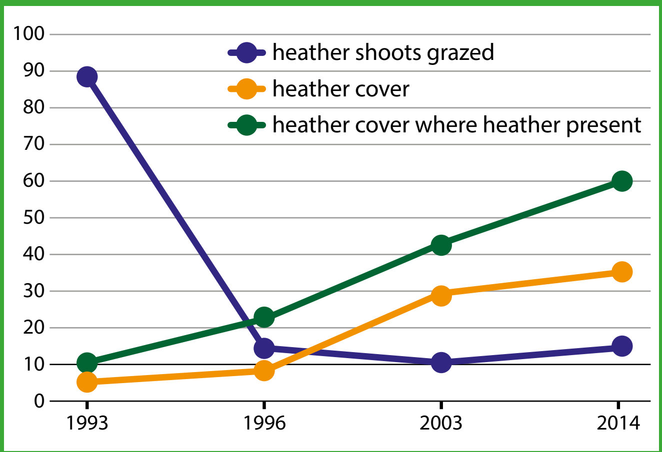

Figure 4: Change in percentage of heather shoots grazed and heather cover at Winsford Allotment plateau 1993–2014. Data from Darlaston & Glaves (2004) and ADAS & Natural England (2017).

Other moorland restoration work, including rewetting of wet heath, more widely across Exmoor has resulted in wider ecosystem service benefits including reduced storm water flow and improved water quality in watercourses draining moorland catchments[57]. Information regarding the restoration of peatlands, which is outside the scope of this chapter, can be found in *Chapter 3*.

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PEATLANDS

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1. KEY POINTS

1. Peatlands are the most carbon-dense terrestrial systems globally; they are home to rare species and support a highly distinctive biodiversity.
2. Many birds, mammals, invertebrates and plants found in peatlands are specialised to some degree, and therefore dependent on the existence of these habitats.
3. The United Kingdom's peatlands contain around 3,000 million tonnes of carbon. However, much of the UK's 2.6 million hectares of peatland is no longer actively sequestering carbon and estimates suggest that UK peatlands could be emitting 23 million tonnes of CO_2e annually.
4. It is possible to return a proportion of these degraded areas to peat-accumulating habitats, through restoration processes, which involves rewetting and revegetation. Improvement of peatlands in this way is a permitted practice for reducing greenhouse gas emissions (GHGs) in any national GHG accounting systems, agreed by the International Panel on Climate Change.
5. Restoration and revegetation can slow the flow of water during some storm events and regulate catchment water flows during dry periods. Peatlands can also act as a nature-based solution for improved drinking water quality.
6. Trade-offs need negotiating between current land-uses and re-establishing and maintaining peatland ecosystems.

2. INTRODUCTION

Peatland ecosystems are wetland habitats with a substrate of semi-decomposed organic matter, or peat. More specifically an area is often considered to be a peatland if the substrate consists of over 30% organic matter to a depth of greater than 30 cm[1,2,[1]]. Covering almost three million hectares (ha), existing peatlands make-up around 10% of the UK land area[3,4,5,6] and consist of three main types: blanket bog, raised bog and fens[6]. They are the most carbon-dense terrestrial systems on the planet; they are home to rare species and support a highly distinctive biodiversity. In certain situations, they can help prevent the flooding of conurbations[7] they influence water quality[8], and have important historical and social connections[9].

There is scope for the UK's peatlands to be used more widely as nature-based solutions (NbS) to mitigate and adapt to our changing climate and help biodiversity to recover. Fundamentally, it is clear that for the UK's bogs and fens to be utilised in such environmentally beneficial ways they must be kept in, or returned to, a healthy ecological state. They need to be kept wet – because peat only accumulates and stores carbon in the long-term because the organic matter is waterlogged – with appropriate vegetation growing on them, and the peat they contain must not be lost through erosion or anthropogenic removal. Although all peatlands have the potential to be a NbS, the location of the ecosystem, type, ecological quality or level of degradation and many other factors will determine the extent of each benefit and solution.

3. CLIMATE CHANGE MITIGATION POTENTIAL

Globally, northern peatlands (north of 45° North[11]) have been estimated to store between 600 and 1,055 billion tonnes[10,11] of carbon. This is twice the amount of carbon stored in the biomass of all the world's vegetation combined (including forests) despite only covering a tenth of the global forested area[12].

The UK's peatlands contain approximately 3,000 million tonnes of carbon (t.C)[13,14]. However, much of the UK's 2.6 million hectares (ha) of peatland is no longer actively sequestering carbon[5,15] and first estimates suggest that UK peatlands could be emitting 23 million tonnes of carbon dioxide equivalent (t.CO_2e) each year[15]. Not only is this equivalent to approximately half the amount released through the nation's agricultural sector[[2]16], but emissions from the extensive areas of peat soil subject to lowland arable agriculture currently make one of, if not the greatest, contributions to UK land-use carbon emission[15].

This switch from a carbon sink to a source is mainly due to current and historic damage inflicted on peatlands through drainage, air pollution, fire, overgrazing, peat extraction for fuel and horticulture, and other land-use pressures[17,5,18,19,20,21]. Indeed, only 20% of the UK's peatlands are considered in a "near-natural" state[22]. The remaining 80% have been modified as a result of past and present management[18,5], with some practices leading to loss or degradation of the peat ecosystem.

It is possible to return most of these degraded areas to peat-accumulating habitats through restoration processes, which involves rewetting and revegetating. Improvement of peatlands in this way is a permitted practice for reducing greenhouse gas emissions (GHGs) in all national GHG accounting systems agreed by the International Panel on Climate Change (IPCC) in 2006, and methods for reporting peatland emissions and removals were described in detail

[1] It is worth noting that there are a range of definitions of what constitute peatlands and 'deep peat' depending on the context.
[2] Based on total UK agricultural GHG emissions of approximately 45 million t.CO2e (Hopkins and Lobley, 2009).

in the IPCC 2013 Wetland Supplement[23]. It has been estimated that peatland restoration can save between two and 19 t.C/ha/yr depending on the quality the peatland is restored to[24]. The ability of peatlands to sequester carbon for millennial time-periods has led to suggestions that they could be at the forefront of so-called "carbon farming" projects or new opportunities for sustainable farming on peat soils – termed 'paludiculture'[25,26,27,28,29].

Despite the consistent and rational desire for more long-term, wide-reaching and interdisciplinary research on peatland ecology, it is clear the management of peatlands offer a significant NbS to tackle rising GHGs. This is both in terms of minimising their current emissions of high levels of GHGs, and increasing their carbon sequestration potential, which although often combined, are two separate factors.

Programmes such as the Peatland Code (voluntary certification standard operating in a similar way to the established Woodland Carbon Code) and methods for active GHG removal could be utilised to maximise peatlands' role. However, financial and training support is needed to enable agencies and partnerships to develop projects and create management plans for validation under the Peatland Code to make them market ready.

In 2020 the Scottish Government announced a £250 million ten-year funding package to support the restoration of 250,000 ha of degraded peat by 2030[30]. This is a positive step as, to ensure investment in peatland restoration is not undermined, land managers need to see policy reinforcing the view of peatlands as valuable assets to society. Future public funds (e.g. the £640 million Nature for Climate Fund and subsequently the Environmental Land Management schemes in England) should also be made available to support recovering and healthy peatlands, and contradictory initiatives that damage peatlands, such as expanding UK tree cover across peatland landscapes, should be avoided. See *Chapter 10: Delivering Nature-based Solutions* and *Chapter 11: Economic Valuation and Investment Options for Implementing Nature-based Solutions* for further discussion.

4. CLIMATE CHANGE ADAPTATION POTENTIAL

Alongside acting as a major UK carbon store, peatlands can act as NbS to help adapt to a changing climate by acting as Natural Flood Management (NFM) systems. Although more research needs to be conducted to evaluate the full potential of peatlands across different catchments, it is clear that restoring (including the blocking of drainage ditches) and revegetating (through the re-introduction of *Sphagnum* moss) can slow the flow of water during some storm events[6,7,31]. Areas of lowland wetland that are designed to flood during high river flows ('washlands') have formed part of the hydrological management of areas such as the East Anglian Fens for hundreds of years, helping to protect urban areas and farmland from flooding. The expansion of these areas, for example as part of restoration or paludiculture projects[3], could increase resilience to more extreme flood events in future[29].

Peatland ecosystems that are in good condition are undoubtedly more resilient to climatic changes because they possess a number of responsive feedback processes, ranging from alteration of the peat-forming species composition[32] to physical alteration of the peat body[33,34]. This helps buffer many species of peatland wildlife against short- to medium-term changes. Waterlogged peatlands dominated by *Sphagnum* mosses could be a NbS for reducing damaging and GHG-producing wildfires, as they are potentially at lower risk of, and see lower severity and impact from, wildfires than both damaged, non-vegetated peatlands, and drier peatlands with a greater vegetative fuel load. Lower water levels lead to drying out of surface peat soils, a fuel in itself, and increasing domination by shrubby vegetation that has much greater amounts of flammable woody biomass[35].

[3] Biomass production on wet peatlands (Tan, Z.D., Lupascu, M. and Wijedasa, L.S. (2021) Paludiculture as a sustainable land use alternative for tropical peatlands: A review. *Science of the Total Environment.* 753).

Some peat-climate models predict that a changing climate could reduce the climatic resilience of certain peatland types across the UK[19]. However, the presence of similar types much further south in Europe[36] suggests that such scenarios are unlikely in the foreseeable future, although the models do highlight the urgent need to restore UK peatlands to good ecological condition in order to ensure that the necessary mechanisms of resilience are in place.

5. BIODIVERSITY VALUE

Peatlands are highly valued for their biodiversity, both at a national level as well as internationally. Some plant assemblages are better represented in UK peatlands than anywhere else worldwide[37]. The UK Biodiversity Action Plan (UK BAP) lists upland flushes, fens and swamps, lowland raised bogs, blanket bog and lowland fens as Priority Habitats, due to their extent, and their lack of fragmentation[37,38].

The highly distinctive conditions created by most UK peatlands (water-logged, acidic, low nutrient[39,40]) mean many species of birds (e.g. the golden plover and hen harrier), mammals, invertebrates and plants found in them are specialised to some degree, and therefore dependent on the existence of these habitats[37]. Some of these species are regionally or nationally rare, such as the large heath butterfly and the swallowtail butterfly, which feeds on milk parsley and is restricted to the peatlands of the Norfolk Broads. Meanwhile peatlands form the main centre of distributions for all our carnivorous plants – an adaptation driven by the low nutrient levels typically available from peat soils – the sundews *(Drosera* sp.) in particular being a source of considerable fascination for Charles Darwin[41].

Active bog is characterised in part by an abundance of bog moss – *Sphagnum*[37] which has a role in climate change mitigation and adaptation potential and is extensive across UK peatlands. *Sphagnum* is vital to the functioning of active peatlands and plays a large role in carbon sequestration, as well as helping moderate water flow[37]. *Sphagnum*-dominated vegetation also suppresses methane release more effectively than vegetation dominated by vascular plants[37,42] and therefore,*Sphagnum*-rich natural peatlands are likely to be beneficial in tackling climate change.

There is therefore scope for the UK's peatlands to be used as a NbS to not only prevent the decline of rare and specialised species, but also to enhance biodiversity through improving or expanding peatland habitats.

6. TRADE-OFFS

The pressures facing upland bogs, raised bogs and lowland fens are different, but all currently have significant issues requiring agreement over the trade-off between current land-uses and re-establishing and maintaining peatland ecosystems.

For instance, the desire to expand the country's forest cover to meet Net Zero targets means some shallow upland peats could be targeted for tree-planting or forest management, schemes. Planting on peat that is deeper than 50 cm is now outlawed under the UK Forestry Standard, but planting on shallow peat continues, supported by evidence that these plantations can sequester carbon over the production cycle if the productivity is high enough. However, modelling suggests that peats should be avoided altogether to avoid damaging the soil, and that new plantations should be created in low-grade agricultural land instead[43] (see *Chapter 1: Woodlands* for further detail). Aside from potential tree planting initiatives, there are further pressures on these landscapes as our upland bog landscapes are targeted for windfarm developments, whilst sheep farming and grouse shooting practices can also alter their NbS capabilities.

There is discussion on the full effects of burning as a management practice on some peatlands, in particular upland bogs. Factors such as burn intensity, frequency, area covered, vegetation structure, time of year, and the degradation status of the peatland all play a part in the resulting changes to biodiversity and carbon sequestering ability of the peat following a burning programme. More studies, taking into account these aspects, need to be conducted to further understand the impacts of fire on a range of peatland habitats. However, the balance of evidence suggests that burn-management has a negative impact on peat carbon accumulation, and on this basis burning should be avoided on peatlands such as blanket bogs.

In the lowlands, the majority of the peatland area has been converted to agriculture, and while these areas are large sources of GHGs – and in some areas now below sea-level as a result of peat wastage – they also comprise some of the more important agricultural land in the UK. For example, the East Anglian Fens hold 50% of the Grade 1 agricultural land in England, contribute an annual £3 billion to the UK economy and 33% of England's fresh vegetables are grown there[44]. Developing these highly productive areas from drained to sustainably managed, wetland peat soils will have major implications for their economic uses with a shift to wetland agriculture. This will change their contribution to national food supply, which needs to be factored into wider agricultural planning. Addressing this acute trade-off represents a major challenge for future UK peatland management and is the focus of Defra's Lowland Agricultural Peatland Task Force in England.

There are issues in the lowland fens regarding the expansion of housing and general infrastructure, leading to disruption of catchment hydrologies for fen systems. Pressure from groundwater abstraction schemes leads to loss of groundwater for fen systems, and nutrient run-off from farming and urban activities is also a threat.

The realisation of the variety and impact of NbS provided by healthy peatland ecosystems – in particular carbon sequestration – will hopefully support their implementation, potentially with the aid of initiatives such as the Peatland Code (discussed further in *Chapter 11: Economic Valuation and Investment Options for Implementing Nature-based Solutions*) and upcoming changes to agricultural payment schemes. Unfortunately, restoration and management practices of peatlands are often not as visible to the public as activities such as tree planting or river restoration, and some of the NbS provided by peats, such as removal and storage of GHGs, are not immediately obvious. Providing policymakers with a robust evidence-base and helping raise public awareness of the importance of peatlands is therefore essential if rational decisions on the necessary trade-offs are to be made.

7. HUMAN WELLBEING VALUE

Peatlands dominate the majority of the UK's National Parks and they are an integral – though often largely overlooked - part of the British countryside - being considered by many as one of the nation's few truly "wild" habitats. Indeed there are around 90 million visits a year to sites rich in peatlands, with people visiting for a variety of recreational activities, from the sedate to the extreme[37]. Expansive peatland landscapes allow access to comparative wilderness which can boost physical and mental wellbeing[6].

From a human health perspective, another benefit to having healthy peatlands is their ability to act as a NbS for improved drinking water quality. Around 70% of the UK's drinking water originates from upland catchments, many of which include peatland habitat[45,46,47]. Peatlands do naturally produce water with a high concentration of dissolved organic carbon (DOC), which requires treatment to remove. However, water from peatlands in good condition is often low in most other solutes, including nutrients, as well as inorganic sediments and particulate organic carbon (POC)[48]. Draining of peatlands tends to further increase DOC and POC[49,50], as well as leading to the acidification of catchment waters, and mobilisation of toxic metals formerly locked within the peat[51,52,53,54]. Water companies must then invest significant resources and energy in removing contaminants before the public drinks it[55] (see Case Study 3). Nevertheless, compared to many other water sources, water derived from good condition peatlands requires relatively little treatment before it is deemed potable. Correct management of peatlands can therefore be beneficial for raw water quality and treatability[48] alongside other human benefits, such as natural flood management, which will be increasingly important under a changing climate.

Aside from this, our peatlands are windows to our past; both environmentally and culturally. The low decomposition rates found in peat mean that grains of pollen, remains of plants and invertebrates, and even – to a certain degree – DNA, are preserved, allowing a profiling of ecological conditions over thousands of years. The same preserving qualities ensure that peatlands are a treasure trove of archaeological finds from timbers and pottery, to fabrics and even human bodies.

Our bogs and fens have also been an inspiration for countless artists and scholars throughout the centuries. Peatlands feature regularly throughout written, spoken and visual media, albeit often not in a positive light – think of Tolkien's Dead Marshes in Lord of the Rings or the Great Grimpen Mire (an actual place, albeit with a different name) in Conan Doyle's Hound of the Baskervilles. Indeed, peatlands have infiltrated our very language, again very often with negative connotations, "she's swamped with work", "I'm bogged down with this", yet these places were once highly revered, with objects of great beauty and value being placed within the peat as votive offerings until as late as the Iron Age.

CASE STUDY 1: WELSH PEATLAND SUSTAINABLE MANAGEMENT SCHEME PROJECT

Peatland covers approximately 21% of Wales[6] and stores an estimated 196 million tonnes of carbon[56]. Most of this peat is classed as shallow peat, but >90,000 ha (4.3% of the total land area) is deep peat (>40cm)[57]. Over 70% of Welsh peatlands are negatively impacted by one or more land-use activity, and in their current condition are estimated to emit around 510 thousand t.CO_2e/yr. Most of these emissions (approximately 67%) are from peatland habitats converted to extensive or intensive grassland[15], with a further 17% approximately emitted from peatlands converted to woodlands and approximately 15% from peatlands in a semi-natural condition (Figure 1).

The Welsh Peatland Sustainable Management Scheme (SMS) project[4] (2017-2021) aimed to reduce emissions from peatlands across Wales through over 670ha of peatland restoration. This project worked on a range of peatland types and condition categories, including >165ha of afforested peat and >500ha of grass-dominated peatlands across 14 sites in Wales through works including conifer plantation felling and invasive scrub removal, erosion gully and drainage channel blocking; reprofiling bare peat 'haggs' (see Figure 3) plus sustainable management of sites through introduction of appropriate grazing management and addressing conifer re-generation.

Funding is a limiting factor and whilst it is sometimes available for initial restoration works, further funding is required to maintain the recovery trajectories initiated by restoration and improved delivery of societal benefits that peatlands in good condition can provide. Funding for such ongoing management can be generated through payment for ecosystem services or carbon finance schemes such as the Peatland Code, a voluntary certification standard to market the climate benefits of peatland restoration. Through 'validating' the reduced carbon emissions at a site over a minimum of 30 years, the carbon that would otherwise have been lost (had the site not been restored) can be sold on the voluntary carbon market and funding generated put towards site maintenance and management to ensure good quality, well-functioning peatlands for decades to come. The Welsh Peatland SMS pioneered and innovated the use of the Peatland Code in Wales with five sites 'validated'.

[4] Welsh Peatland SMS is a £1 million Wales-wide partnership project funded by the Welsh Government and European Union to help achieve the Ministerial ambition of bringing all of Wales' peatlands into sustainable management by 2030.

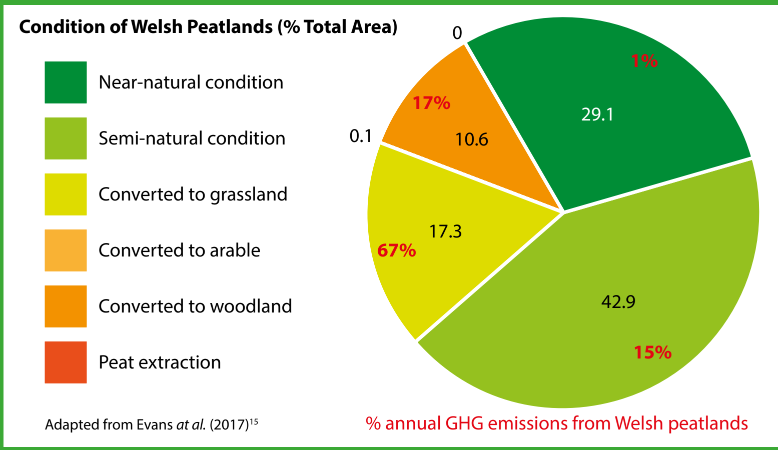

Figure 1: Summary of peatland condition in Wales and relative greenhouse gas emissions (CO2, NH4, and N2O) from each condition state. 'Near-natural condition' includes peatlands in poor condition with the National Peatland Action Programme stating "it is estimated that no more than 10% by area of the near-natural and modified peatland resource is likely to be in favourable condition"[58].

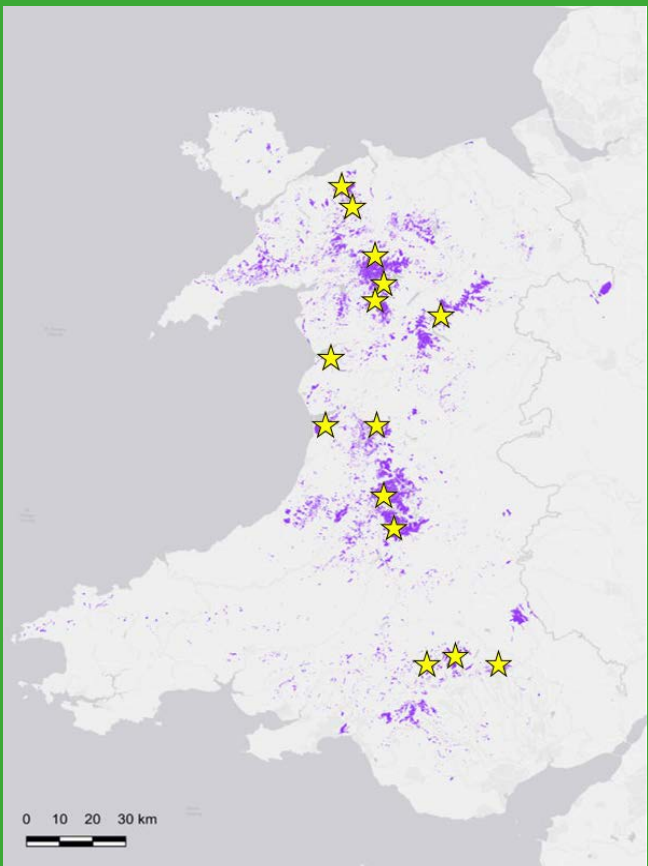

Figure 2: Distribution of deep peat soils in Wales (>40cm, purple) and location of Welsh Peatland SMS Project restoration sites (stars): one is lowland raised bog site and the remainder upland blanket bogs sites, including four afforested sites. © Welsh Peatlands SMS Project

Figure 3: Reprofiling of bare and eroding peat 'Haggs' to enable vegetation establishment of these bare peat 'faces' and provide protection of the carbon store. Images: © Welsh Peatlands SMS Project

CASE STUDY 2: NATURAL FLOOD MANAGEMENT BENEFITS OF PEATLAND RESTORATION

The expansive areas of bare peat covering the headwater catchment areas in the South Pennine Moors Special Area of Conservation (SAC) have long been associated with increased overland flow and flashy response to rain events. There was a dearth of strong evidence but a long history of flooding. In 2009 Moors for the Future Partnership, in collaboration with the Universities of Manchester, Leeds and Durham, established a project to test the Natural Flood Management (NFM) benefits of the ecological restoration of bare and eroding blanket bog habitat in the South Pennine Moors SAC.

The ecological restoration method included blocking deep erosion gullies using timber and stone dams and the revegetation of bare peat with a grass crop that provided temporary stabilisation of the peat mass and subsequent diversification to a community typical of blanket bogs, supported through planting *Sphagnum* mosses, sedges and species of dwarf shrub (see Figure 4).

Four years after the restoration intervention, re-vegetation resulted in a 106% increase in the time from peak storm rainfall on the peatland headwater catchment to peak water flows leaving the same catchment relative to the control, and a 27% reduction in the peak flows from the catchment relative to the control[6]. These effects persisted in the most extreme rainfall conditions within the available dataset, albeit at a reduced level. There was also no change in the proportion of rainfall leaving the catchment in a storm associated with the restoration, indicating that the post-restoration reductions in peak flow and associated hydrograph changes are not attributable to increased catchment storage, but slowing of water flows.

Water flow velocities are slower through *Sphagnum* than through grass/sedge vegetation[7]. As *Sphagnum* becomes established, additional benefits are likely to be realised and will be evidenced. Research is ongoing with funding in place to continue until 2021, nine years post stabilisation and six years after *Sphagnum* application.

Links:

- Moors for the Future Partnership: Making Space for Water Project
  https://www.moorsforthefuture.org.uk/our-work/our-projects/making-space-for-water
- University of Manchester: NERC Protect Project
  https://protectnfm.com/about/
- Environment Agency: Working with natural processes to reduce flood risk
  https://www.gov.uk/government/publications/working-with-natural-processes-to-reduce-flood-risk
- Working with Natural Processes – Evidence Directory [See: Headwater drainage management – link to a Moors for Future Partnership case study]
  https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/681411/Working_with_natural_processes_evidence_directory.pdf
- IUCN UK Peatland Programme Commission of Enquiry: Peatlands and Natural Flood Management
  https://www.iucn-uk-peatlandprogramme.org/sites/default/files/header-images/Resources/COI%20Catchments%20briefing.pdf

Figure 4: Before, and short-term recovery; After initial restoration works on blanket bog on the Pennine hills above Greater Manchester. Revegetating bare peat significantly slows the flow of surface water across, and from, peatland in this condition, helping to reduce downstream flood risk from storm events. Images: © Moors for the Future Partnership.

CASE STUDY 3: PEATLANDS IN NORTHERN IRELAND: GARRON PLATEAU

Approximately 12% of the land area of Northern Ireland is covered by peatland[59]. However, even within designated sites, much of Northern Ireland's peatlands are in unfavourable condition[59] and only as little as 1% has been restored in the past 30 years[60].

The Garron Plateau in County Antrim is the largest area of blanket bog in Northern Ireland at 4,650 hectares[59] and supports a number of rare and notable plant and animal species[61], including priority species like hen harriers and merlins[59]. It is designated as a Special Area of Conservation and an Area of Special Scientific Interest (ASSI)[59,61] due to the presence of blanket bog, lakes and fens among other features. Additionally, this landscape also provides drinking water for almost 12,000 homes and businesses in the local vicinity[59].

Historically this bog was drained and overgrazed which led to a fall in the water table, drying of the peatlands and erosion[59]. Among other problems, Northern Ireland Water (NIW) have since invested in restoring the site condition. Through the Cooperation Across Biodiversity Borders project, NIW have worked in partnership with the Northern Ireland Environment Agency and RSPB NI to undertake a variety of restoration activities to improve the site condition for nature, sequester carbon and improve water quality.

This work included reducing grazing densities[62] and installing over 1,000 peat, wooden and stone dams to block drains at the Garron Plateau. The project has helped restore natural hydrological conditions and promote the colonisation by *Sphagnum* moss[62], a core component of a functioning bog, and as the habitat is restored, a range of other plants and animals will benefit[59]. Furthermore, as a result of this project, emissions of 1,992 tonnes of CO_2e annually will be avoided[60]. There has also been an improvement in the raw water quality coming

Image 1: Garron Plateau. Image: © Darren Houston.

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GRASSLANDS

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1. KEY POINTS

1. Over 40% of land cover in the United Kingdom (UK) is grassland. Currently, only 2% of the UK's grassland cover comprises of biodiverse carbon rich semi-natural grassland. Protecting this grassland is of high importance for biodiversity and avoided emissions.
2. Acid grasslands, predominantly found in the uplands, contain around 30% more soil carbon per unit area than other grassland types. Neutral (semi-improved) grasslands, richer in species than improved grasslands also contain marginally more soil carbon in the top 15cm of soil. Maintaining and improving species diversity in neutral grassland is critical for mitigating greenhouse gas (GHG) emissions and increasing wider biodiversity.
3. Restoring permanent grassland via reversion from improved grassland or arable land, including the restoration of wet or chalk grasslands as part of a varied mosaic style landscape, can positively impact biodiversity and reduce GHG emissions. For example, figures from the UK Land Use, Land Use Change and Forestry (LULUCF) GHG inventory indicate that conversion of arable land to grassland has the potential for removing 8.72 million tonnes of carbon dioxide (CO_2) per hectare per year (t.CO_2/ha/yr) across the UK.[1] In contrast, conversion of grassland to arable land can result in net emissions of 14.29 megatons (Mt.CO_2e/ha/yr)[1].
4. Further research is needed to identify optimal sward composition, structure and associated grazing practices for GHG mitigation and enhanced grassland biodiversity which fit with production needs on intensively managed grassland. Continuous set stocking may result in reduced carbon sequestration and biodiversity and associated impacts on ecosystem services, including water-holding capacity.
5. Some types of grassland may be suitable for carefully selected tree planting with native species, e.g. for agroforestry or wood pasture. Agroforestry has the potential to mitigate climate change through increased carbon sequestration in vegetation and soils, storing up to 63 tonnes of carbon per hectare in temperate regions.[2] However, a good understanding of site characteristics including vegetation communities, soil carbon at depth and hydrology is essential to avoid perverse outcomes.
6. As well as decreasing animal numbers overall, grazing by a diverse range of animals (e.g. sheep, cattle, horse, goats, alpaca) on the same pastures can also have positive effects on grassland sward diversity and resultant GHG emissions[3]. Shifts in grazing patterns, for example the adoption of rotational or mixed grazing, can also reduce emissions compared to continuous grazing[4].

2. INTRODUCTION

Effectively managed healthy grassland ecosystems can provide vital environmental, social, cultural and economic benefits[5,6,7]. Grassland covers almost 40% of the UK land area[8,9] and is generally classified into lowland (below 350m) and upland types[1]. The lowlands tend to be drier and less exposed than the generally wetter and cooler uplands[10]. Grasslands vary from intensively managed agriculturally improved grasslands and arable leys in lowland agricultural areas, through a range of semi-improved grasslands (usually ploughed and sown at some stage) to semi-natural grasslands on neutral, acidic and calcareous soils. Grazing pastures tend to be significant for both food production and the ecosystem functions and services which they provide, whilst meadows are primarily associated with production of the latter[11,12]. Grasslands that are not cultivated and re-sown within five to seven years or more are generally defined as permanent grassland; those that are cultivated within this period are classified as temporary grassland[13,14].

Grasslands in the UK are almost entirely under agricultural management. Therefore the future design of Environmental Land Management Schemes (ELMS) (as currently being tested and trialled in England) and other devolved nations agri-environment schemes[15,16], which will replace the Common Agricultural Policy (CAP) will play a crucial role in deciding the extent to which grasslands can fulfil their potential as nature-based solutions (NbS).

The future provision of ecosystem services[5] and public goods from grasslands needs to be addressed through appropriate management interventions. Where possible this will create win-wins for both food production and the provision of wider public goods. The following sections focus on human wellbeing, the biodiversity value of grasslands and practices that can help to address issues affecting climate change mitigation and adaptation, whilst ensuring effective management and maintaining food production.

3. HUMAN WELLBEING VALUE

Semi-natural grasslands are of significant cultural importance for the UK[17]. They cover such a large extent of our landscape, including areas of key importance for human access such as our National Parks[12]. Twenty eight percent of UK National Parks and Areas of Outstanding Natural Beauty (AONB) consist of semi-natural grasslands[18]. For example, the North Pennines in England which contain 40% of the UKs upland hay meadows. Grassland can deliver cultural, biodiversity and climate benefits for a region. For example, County Fermanagh in Northern Ireland has semi-natural, species rich wet grassland concentrated in the area, but is not designated as an AONB or National Park[19,20].

Grassland characterises many UK landscapes. For example, UNESCO world heritage sites and extensive areas of the Lake District[21]. National Parks are rated as important for human wellbeing by the UK public[22]. However, they are often criticised for failing biodiversity. This can be due to high visitor numbers and management practices and policies that focus on cultural landscape value[23,24]. Despite sometimes damaging practices, like sheep overgrazing[25], grasslands remain important habitats for biodiversity. For example, they provide breeding sites for wading birds, such as Curlews which are in decline across the UK[26,27].

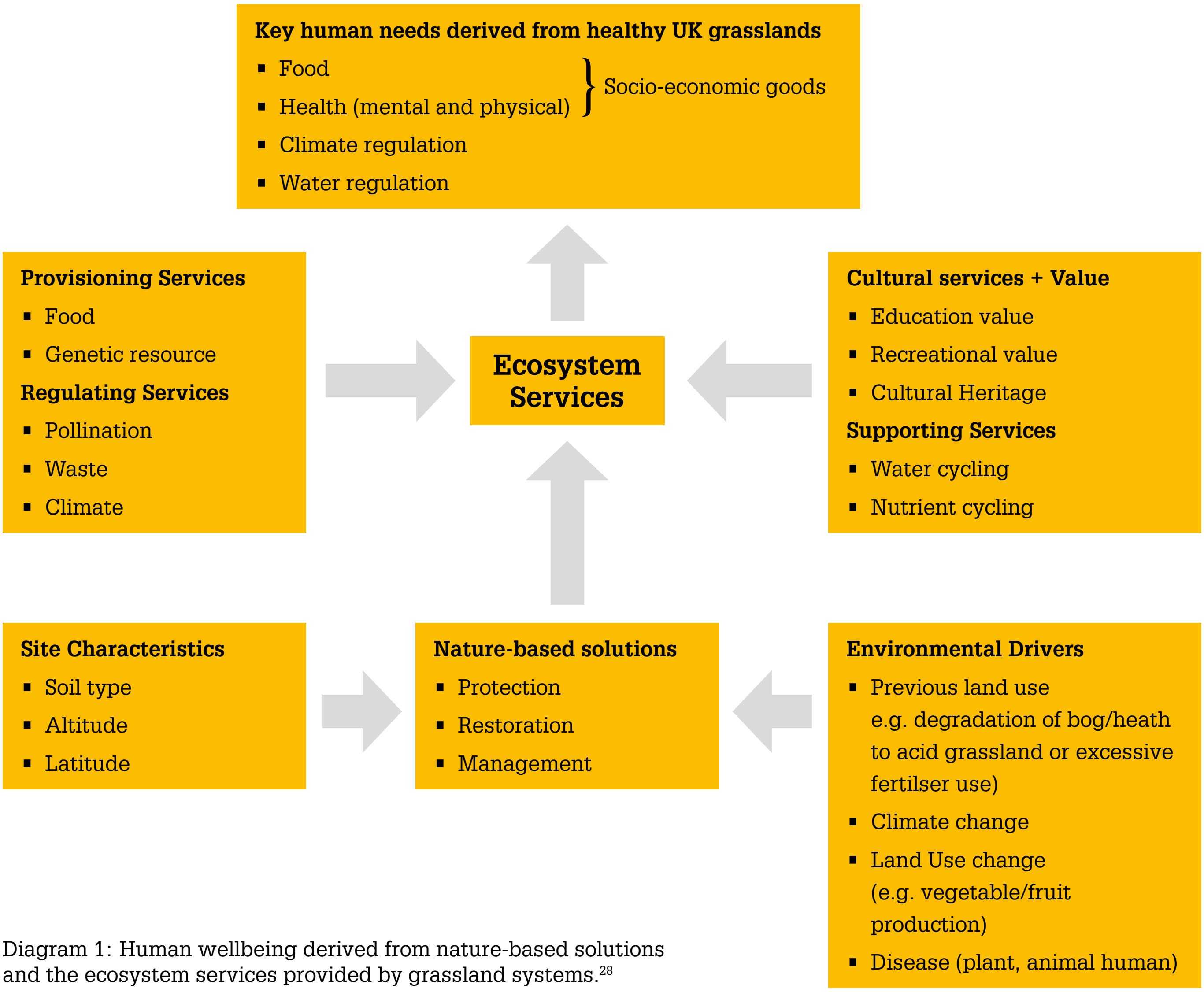

Diagram 1: Human wellbeing derived from nature-based solutions and the ecosystem services provided by grassland systems.[28]

4. BIODIVERSITY VALUE

There was an estimated 97% loss of enclosed semi-natural grasslands in England and Wales between 1930 and 1984, with only 2% of the remaining UK's current grassland area considered to have a high diversity[12]. In lowland meadows and pastures up to 35 or more plant species may occur in a 2m x 2m sample, including a range of grasses and herbs, e.g., Knapweed (*Centaurea nigra*) and Bird's-foot trefoil (*Lotus corniculatus*) and in some meadows, rarer species like Snake's Head Fritillary (*Fritillaria meleagris*)[18,29]. Well established lowland meadows provide excellent habitat for invertebrates, such as butterflies and other pollinating species, which has a direct value for food security[30].

Grasslands also provide important habitats for many British fungi that provide decomposition benefits for the soil[31,32]. Many species of fungi thrive in nutrient poor semi-natural grasslands. The UK's Waxcap mushroom species are dependent on grasslands in Wales, Scotland and Northern Ireland in particular[33,34,32]. Many of these high value semi-natural grasslands are now under protection from conservation charities or within national nature reserves where they may be managed by conservation grazing under agri-environment schemes. There are also 122 endemic vascular plant species in Britain that rely on grasslands for their habitat[35].

Semi-improved and improved grasslands tend to be less biodiverse than semi-natural grassland, largely due to management influences including ploughing and sowing with productive species, the use of fertilisers (organic and mineral) and intensive grazing management[36,37]. However, their extent means that they remain important habitats for many of our common species. For example, they provide crucial feeding areas for wintering birds such as Fieldfare (*Turdus pilaris)*, Redwing (*T. iliacus*) and other farmland birds[18,27].

While the UK's 'landscape designations' (such as National Parks and AONBs) contain a significant proportion of the UK's upland grasslands, many are not designated specifically for nature conservation and do not necessarily contain high amounts of biodiversity. They do remain important for carbon storage a high percentage of UK carbon stock is located within our soils[7]. Designated landscapes may include high concentrations of sites designated for nature within them, such as Sites of Special Scientific Interest (SSSI) or Areas of Special Scientific Interest (ASSI). However, these are often in poorer condition, in terms of biodiversity, than SSSIs in the countryside outside of designated landscapes[38,23]. For grasslands this has in many cases been attributed to overgrazing.

5. CLIMATE CHANGE MITIGATION POTENTIAL

5.1 RETAINING PERMANENT GRASSLAND IN SITU

Grasslands store carbon below ground and due to their large coverage they hold a considerable proportion of the UK carbon stock. Acid grasslands, predominantly found in the uplands, contain almost four times as much soil carbon in the top 15cm of soil than other grassland types. However they are considerably less dense than either neutral (semi-improved), or improved grasslands resulting in stocks of soil carbon being around 30% higher in acid grassland. Neutral or semi-improved grasslands contain around 15-20% more soil carbon than improved grasslands in the top 15cm. However they are also less dense leading to only marginally higher soil carbon per unit area on neutral grasslands[8]. The UK Land Cover Change product for 1990-2015 shows losses of 7668km^2 of grassland across the UK over that time period.[39] Whilst the definition used to assess this change is broad (due to use of satellite data), this loss of grassland is of concern, particularly where grassland is being lost to less carbon rich arable or urban areas.

Whilst we still do not fully understand the processes involved in carbon storage and sequestration at depth, we know that habitat loss can lead to GHG emissions. For example, protecting permanent grassland from conversion to croplands strongly mitigates against the loss of soil carbon[40]. Similarly, reducing the incidences and/or frequency of ploughing-tilling and reseeding on improved grasslands could impact significantly on soil carbon stocks and overall GHG emissions.[41] In contrast, the conversion of croplands to more permanent grasslands can enhance soil carbon sequestration[42].

Different estimates of habitat loss across the period from 1930 to 2016 indicate that up to 97% of semi-natural grassland has been lost[43], that it remains in significant decline in some areas[1] and is highly fragmented everywhere. Habitat losses for semi-natural grassland are considered to be more likely to be significant for diminishing carbon stocks than management factors[1,44]. A small proportion of semi-natural grasslands may now be owned and managed for conservation, e.g Chinnor Hill owned and managed by the Wildlife Trusts, and maintenance and protection of these biodiverse, carbon-storing habitats continues to be of key importance. Similarly, grasslands that have a high carbon stock (but may not necessarily be species rich), including acid grassland in upland areas on peat soils, should also be protected (or where appropriate, restored to former bog habitat) and soil disturbance minimised.

Traditional management of semi-improved/ improved grassland, including ploughing and re-seeding every five to eight years with simple species mixes (and more frequently than that for leys on arable land), results in net losses of soil carbon[13,7] Shallow rooting depths of sown species (e.g. annual ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*))[45,46] constrain soil carbon[14] and have low levels of species diversity. This management model was targeted primarily at increasing productivity, with grass (usually *Lolium perenne*) as the main crop species. They are often enhanced by nutrient inputs, which themselves affect GHG mitigation through N_20 emissions, the fertiliser manufacturing process and their application. This management model also reduces the diversity of species that are present.[47]

Organic inputs like slurry and mineral fertilisers and, to a lesser extent, farmyard manure (FYM), can significantly increase soil CO_2 and N_2O emissions (although FYM may also constitute a significant carbon input). The effect is highly dependent on the fertiliser used and the timing and type of application. Increasing soil pH through liming can reduce N_2O production, as production is higher in acidic grassland soils generally[48].

In addition to emissions of GHG pollutants from agricultural grasslands, losses of phosphorus (P) and nitrogen (N) due to fertiliser application and, for P in particular, nutrient rich animal waste, remain a key source of diffuse pollution in UK water bodies[49]. A shift away from traditional ploughing and reseeding practices and associated nutrient management practices, towards practices using more diverse permanent pastures which require lower levels of nutrients, would better enable grasslands to fulfil their potential as an NbS for climate mitigation and biodiversity enhancement. It is however, very important to establish whether there would be a the trade-off between food production and a focus on public goods that would result from such a management change.

An additional pressure on grassland is tree planting. The UK Land Cover Change product for 1990-2015 indicated that whilst open grassland habitats decreased over that time period, woodland increased[50]. Going forward, most of the land identified as suitable for tree planting in the UK is grassland[51,52]. Tree planting may have significant impacts on all grassland types from improved grassland to grassland habitats protected by law for their ecological, scientific, scenic, or cultural value[51]. Some evidence suggests that planting trees on grassland can have temporary negative impacts on soil carbon[53]. This is because site preparation for planting trees releases carbon from the soil[54]. This initially creates a "carbon debt" which may be small, but needs to be repaid before it can deliver any climate benefit[55]. Whilst afforestation is effective at sequestering carbon, impacts are likely to be complex and dependent on a range of interacting factors including soil type, grassland type and management. It can also be dependent on how the trees are planted and what species they are. Similarly, tree planting for climate change mitigation may have positive or negative impacts on biodiversity depending on the above factors and habitat context. While the introduction of trees into pastureland (silvopasture) is likely to be positive for biodiversity[56], outcomes are highly dependent on the starting point of the pasture, with tree planting on species rich semi-natural grasslands likely to be highly damaging to the biodiversity of this now uncommon habitat.

5.2 GRAZING MANAGEMENT

Grazing ruminants on grassland contribute to GHG through the production of methane (CH_4) emissions, primarily from belching (as a result of enteric fermentation) and excreta as well as through the management of the grassland on which they graze[57]. Semi-natural grasslands are generally associated with lower methane and nitrous oxide emissions than agriculturally improved grasslands due to lower stocking densities and inputs.

Appropriate management of grazing animals and the grasslands on which they graze can help to maximise the climate change mitigation potential of UK grasslands. As well as reducing the incidences and/or frequency of ploughing-tilling, reseeding and fertilizer use (above), reductions in the numbers of animals and grazing pressure may help to reduce overall GHG emissions from grasslands[58]. As well as decreasing animal numbers overall, grazing by a diverse range of animals (e.g. sheep, cattle, horse, goats, alpaca) on the same pastures can also have positive effects on grassland sward diversity and resultant GHG emissions[3]. Shifts in grazing patterns, for example the adoption of rotational or mixed grazing, can also reduce emissions compared to continuous grazing[4].

‘Mob grazing’, is a type of grazing management that is attracting a lot of attention in some farming circles, for example, one of the Innovative Farmers groups currently being run by the Soil Association is focused on it. Whilst it is used across a variety of approaches (often with other descriptors), it generally refers to short term, high density grazing which may or may not occur on tall grass but always includes a long recovery time for the pasture to re-grow (both above and below ground) and may result in some trampling of the pasture.

Its use is based on adopting grazing patterns that mimic herd grazing patterns in nature. It has been used under various conditions and on both arable land and rangeland, with evidence from some parts of the world indicating positive benefits for soil health, soil carbon, and plant diversity as well as animal productivity[59,60]. Despite this evidence, as it is a relatively novel practice in the UK, our data set is limited, particularly in terms of understanding potential additional long-term benefits for soil carbon (C) and soil health in comparison to current UK grazing management practices. Hence, more research in this area is required.

6. CLIMATE CHANGE ADAPTATION POTENTIAL

Grassland soils absorb and filter water, cycle nutrients and store carbon on a large scale[13,61] making them a potentially valuable NbS for climate mitigation and adaptation lower density extensive grazing can increase water infiltration rates and reduce flood risks by avoiding soil compaction[62,63]. Grasslands can provide resilience to extreme weather events. For example, chalk grassland can act as a natural buffer to reduce the likely impact of flooding. Grassland can also provide naturally functioning floodplains that can evolve into new wetland habitats and allow for greater water storage[64]. There is evidence that land use change from grassland to wetland can result in sequestration of 2.39 to 14.30 $t.CO_2$/ha/yr[1].

Ecological restoration of grassland sward plant diversity could offer a valuable means to increase the adaptive capacity of UK grasslands to a changing climate[74,7]. The introduction of native species mixtures that include legumes has also been shown to benefit soil carbon sequestration[71,72,73] and to reduce the need for synthetic nitrogen fertilisers. However, the capacity of UK grasslands to naturally adapt to climate change through increasing in species diversity is severely limited by the presence and connectivity of habitats including suitable species in the wider landscape.

Although the variety of grasslands across the UK provides some resilience to environmental drivers, some grassland types, may be more sensitive than others, e.g. hay meadows in the uplands, which may be particularly sensitive to climatic change[74,7]. These meadows may adapt to climate change by transitioning to less notable habitats, but even as wetter grassland they will remain important for carbon and water storage.

7. CHALLENGES

Only 2% of the biodiverse and carbon rich semi-natural grassland that was present in the UK a century ago remains; protecting this grassland is a key priority. Two thirds of UK grassland is intensively managed for agricultural use[8]. Going forward, one of the challenges will be rethinking grassland management practices for the maintenance and enhancement of biodiversity, carbon storage and sequestration, alongside food production. This will include consideration of management practices which affect the production, maintenance and long-term use (grazing, hay, silage) of a productive biodiverse grass sward whilst avoiding excess carbon loss (e.g., ploughing,

CASE STUDY 1: FLOODPLAIN MEADOWS DELIVERING NBS[65,66],

Floodplain meadows are a beautiful and ancient agricultural system that has evolved over many hundreds of years through an annual hay cut followed by aftermath grazing. The result of such management has been the development of communities of grasses and herbs that thrive with the flood and drought cycles on floodplains than against it. Floodplain meadows hold one of the UK's most diverse plant communities, with up to 40 plant species m^{-2}. The Natural Capital of Floodplains (2018)[67] argues that the value of the benefits provided by seasonally inundated floodplain meadows far outweigh those provided by land in intensive agriculture.

From left to right: Floodplain meadows at work © Irina Tatarenko, Belted galloways Clattinger Farm © Mike Dodd and Yarnton meadow Oxfordshire, species rich grassland © Mike Dodd

Floodplain meadows regulate flood events by providing space outside the river channel for floodwater to occupy. They capture sediment, absorb nutrients and filter water, whilst also delivering sustainable agricultural production with minimal inputs, and constituting a rich cultural resource. Their alluvial soils are particularly important for carbon sequestration because they grow deeper with each flood event[68]. In this respect they are probably second only to peat soils in the UK in their ability to store carbon. Organic carbon within the top 10 cm of soil at North Meadow Cricklade (a species-rich floodplain meadow) was observed to be 0.11 tC/yr[69] values much higher than those previously reported for neutral grassland and extensively managed grasslands in a survey of grassland soil carbon[8,44]. The deep rooting strategies and diversity of plants and roots are the keys for carbon storage. Recently published research Tilman 2019[70] comparing carbon storage between species poor swards and species-rich grasslands restored from species- poor swards show that higher species-richness increases the rate of carbon sequestration in grassland communities.

seeding, inputs).

Another challenge for grassland management is the research needed to assist in transforming grassland management. Lack of understanding about the processes leading to carbon storage at depth, its relationship with biodiversity above and below ground and how it is affected by field management practices needs to be addressed. Gaining a better understanding of these processes and how they relate to food production (both quantity and quality[75]), preferably alongside farmers, will help to determine appropriate land management practices in relation to mitigating or reversing biodiversity loss and climate change impacts. For grassland in areas of particular cultural interest (e.g., for tourism, recreation and inspiration), such as the National Parks and AONB's, there is a challenge around how to enhance biodiversity and carbon storage whilst continuing to maintain and enhance these cultural ecosystem services which result in vital income for many of these areas, e.g., maintaining profitable livestock enterprises.

Common sense would suggest that grassland with low carbon stocks and biodiversity both above and below ground is the best land on which to plant trees. Some research on approaches to planting trees on or around grassland for maximising grassland and biodiversity, whilst enhancing or minimising agricultural outputs, is already available[76]. However, to mainstream these and other practices it is likely to be important to work with land managers to gather further evidence across a range of approaches and locations and to understand how to encourage and motivate farmers to take up novel practices. Tree planting on carbon and biodiversity rich grassland or on ecologically important wetlands should be avoided to avoid carbon and biodiversity loss; an understanding of site history and ecology is therefore crucial.

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ARABLE SYSTEMS

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1. KEY POINTS

1. Arable land is under very active management and therefore it offers many opportunities to introduce nature-based solutions (NbS) that enhance natural capital. The UK is at a pivotal moment in the future design of our agricultural systems, as new agricultural policies will have to be designed outside the EU Common Agricultural Policy.
2. **Hedgerows** are already a very important NbS in arable landscapes, with current estimated stocks of up to 100 tonnes of carbon per hectare (t.C/ha) in established hedge networks. Planting of hedges and hedgerow trees along with rejuvenation of hedges through placing them back in management cycles are a low trade-off option for addressing climate change and enhancing biodiversity in arable systems.
3. **Field margins** that are taken out of production benefit wildlife, leading to increased numbers of many wild species, including those that deliver important ecosystem services such as pollination and pest regulation. Soil carbon is 37% higher in soil beneath a grass margin than beneath an annual crop. Field margins can also prevent erosion and water pollution.
4. **Conservation biological control**, or natural pest regulation, has the potential to reduce the need for pesticide use, which could help reduce the approximate 8,300 tonnes carbon dioxide equivalent (CO_2e)[1] involved in the manufacturing of pesticides.
5. **Agroforestry** has the potential to mitigate climate change through increased carbon sequestration in vegetation and soils (up to 63 t.C/ha in temperate regions). It can also improve the climate change resilience of arable landscapes whilst increasing biodiversity and wider landscape diversity.
6. Further research is required to fully understand the benefits of conservation biological control, cover crops and intercropping in terms of climate mitigation and biodiversity.

[1] CO_2e is used to compare the emissions from various greenhouse gases based upon their 100 year global warming potential (Organisation for Economic Co-operation and Development (OECD), Glossary of Statistical Terms, https://stats.oecd.org/glossary/detail.asp?ID=285, 2013)

2. INTRODUCTION

Arable farming accounts for 26% of the 19 million hectares (ha) of agricultural land in the United Kingdom (cereals 17%, other arable 8%, horticulture 1%)[1]. Changing diets as a consequence of increased environmental and animal welfare awareness will require expansion of cropland if we want to increase UK production and avoid offshoring greenhouse gas emissions (GHGs)[2].

Arable land is under very active management, and therefore it offers many opportunities to introduce solutions that enhance natural capital and provide public goods whilst maintaining food production. Across the UK we are at a pivotal moment in the future design of our agricultural policies (e.g. through the Environmental Land Management (ELMs) scheme in England, GLASTIR in Wales, The Agricultural Transformation Programme in Scotland and Northern Ireland's Environmental Farming Scheme (EFS)) as the government channels agricultural subsidies of the EU Common Agricultural Policy away from an area managed approach towards supporting increased environmental benefits.

Whilst there is a range of research on the economic costs and benefits of enhancing degraded agricultural land for wildlife, the results are varied and generalisable information that can be scaled up is not readily available. The present value of the overall benefits expected from agri-environment measures in lowland England was estimated to be £12 billion over 50 years, based on the costs of reducing livestock on grassland, improving former hedgerows and creating pollinator strips[3].

Most recent studies indicate that arable agriculture is responsible for significant GHGs both on and off farm. For example, GHGs are released due to arable soil management which include nitrous oxide (N_2O) from fertiliser use and, methane (CH_4) from ruminant livestock and manure used in mixed arable systems, as well as carbon released due to draining waterlogged soils such as lowland fens[4,5,6]. This needs to be balanced against the potential to close nutrient loops in mixed systems. Biodiversity is profoundly impacted by arable farming with significant reductions in farmland birds, insects and wildflowers[7]. For example, the UK Farmland Bird Indicator has decreased by 48% since 1970[8] and declines in insects have been linked to agricultural practices and land use changes[9]. However, some studies (e.g. Macgregor *et al.*, 2019[10]) do indicate a more variability than a steady decline in biomass so this is an area which needs further investigation.

The following sections highlight nature-based solutions (NbS) that have capacity to sequester and store carbon, increase resilience of agricultural systems to climate change and improve biodiversity, whilst maintaining food production.

3. CLIMATE CHANGE MITIGATION POTENTIAL

This section describes the potential for NbS in arable landscapes to contribute to climate change mitigation through either directly sequestering and storing carbon or indirectly reducing the need for practices that generate GHGs (e.g. pesticide manufacturing).

3.1 HEDGEROWS

Hedgerows are an important NbS, which play a key role in carbon sequestration and storage in arable landscapes[11,12,13]. Above ground, uncut shrubby hedges may accumulate around 1.8 tonnes of carbon dioxide per hectare per year ($t.CO_2/ha/yr$), while tree lines may accumulate more than 11 $t.CO_2/ha/yr$[14]. For established hedge networks, evidence from Britain, Germany and France suggests that hedges may store roughly 100 t.C/ha, although this will vary considerably according to hedge structure, woody species and age[15]. Below ground, both shrubby hedges and tree lines may sequester 1.8 t.CO_2/ha/yr[16]. A meta-analysis of data from 60 studies found that soil carbon stocks are 22% higher under hedgerows and 6% higher next to the hedgerow than in fields without hedgerows[17]. The re-establishment and maintenance of hedgerows was estimated to cost £7,000 per kilometre and have a present value of up to £1 billion[3].

3.2. HERBACEOUS FIELD MARGINS

Field margins are usually two to six metres wide and can be implemented for a variety of reasons including for soil and water conservation and support for pollinators, or general biodiversity support[18]. They can be managed in many ways, including as annually cut grass margins, margins sown with perennial flowering plants, or simply left to naturally regenerate. Margins may also be sown with annual flowering plants or be cultivated annually, but these are not discussed here. It is important to note that field margins should be managed as permanent features to retain their sequestered carbon, unless a no-till approach is followed which avoids disturbing the soil.

Grassy field margins alongside annual crops have 37% higher soil carbon in the upper 30 cm soil layer, compared to arable fields without a grass margin[17]. This effect is partly due to increased plant cover and diversity. Studies in temperate grassland show that increasing plant species diversity increases soil organic matter[19,20,21,22]. Deep rooting herbaceous plants such as tall herbs reduce carbon loss from deeper soils[21] and carbon accumulation increases over time both near the surface and deeper in the soil profile during grassland restoration[22].

Perennial vegetative strips, such as riparian buffer strips or strips alongside other water courses, can reduce soil erosion by filtering sediment and stabilising soils[23]. This may contribute to climate change mitigation directly through carbon sequestration, and indirectly by regulating water flows within and around arable fields, as well as by influencing nitrogen and phosphorus movement.

Minimising soil cultivation in field margins can improve the diversity of soil macrofauna[24] and thereby potentially enhance soil resilience. The balance of the soil community is also important with regards to the climate mitigation potential of field margins, as soil biota are both involved with decomposition processes and the release of GHGs, as well as with the formation of soil organic matter and carbon sequestration[25]. The overall impact of biota on GHGs cannot yet be quantified, and therefore further research is needed to establish their effectiveness to act as a NbS for climate change mitigation.

3.3. CONSERVATION BIOLOGICAL CONTROL

Pesticides, along with plant breeding, are the main methods of pest and pathogen control in the UK arable sector. Pesticides have allowed farms to create simplified landscapes which would otherwise be too vulnerable to pests and pathogens. Unfortunately, while easier to manage when optimising for labour inputs per hectare, these simplified landscapes miss the benefits associated with diverse landscapes through the application of conservation biological control (control of agricultural pests, including insects, plant pathogens and weeds, using naturally-occurring organisms in the agricultural ecosystem). Potential benefits of conservation biological control can include yield gains[72,76] and a reduced requirement for pesticides[75], indirectly reducing the GHGs associated with pesticide manufacturing (approximately 8,300 tonnes CO_2e[2]) which are about 9% of the total associated with UK arable crop production[26]. However, these benefits are not found in every circumstance and more research is needed.

3.4. AGROFORESTRY

Agroforestry is a NbS which integrates trees and shrubs into agricultural systems. It is not widely practiced in the UK. Farm woodlands

[2] Calculation based on: 0.493 kg CO2 emissions to air from average pesticide manufacture (Ecoinvent 3.6 dataset documentation) and the 16,900t of pesticide used in 2016 (https://secure.fera.defra.gov.uk/pusstats/myresults.cfm) against total 45.4 MtCO2e for UK Agriculture in 2018 (https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/862887/2018_Final_greenhouse_gas_emissions_statistical_release.pdf)

outside of the cropped area are more common than systems where trees are integrated into the arable land, although there are notable pioneering examples of agroforestry such as at Whitehall Farm in Cambridgeshire and Parkhill Farm in Fife. Integrated agroforestry systems generally comprise parallel rows of trees or shrubs, with strips of varying width of arable land in between. The choice of trees and crops depends on the local environment. Trees are selected for their economic value, particularly provided by fruits and timber. Crucially, trees also bring value to the arable land through protection against soil erosion, effective utilisation of nutrients via roots and leaf fall and microclimate benefits[27].

The mitigation benefits accrue from the carbon sequestration by the tree component of the system, along with factors like better soil conservation and increased soil organic matter leading to greater carbon storage. Although much of the research evidence for agroforestry derived carbon benefits relate to non-temperate systems, in temperate regions it has been shown that soil carbon in arable land increases with the presence of rows of trees, likely due to the input of tree litter[28]. The average carbon storage by agroforestry systems has been estimated at up to 63 t.C/ha in temperate regions[29]. Trees alongside water courses, can have similar benefits to herbaceous riparian buffer strips preventing erosion and pesticide run off[30].

3.5. COVER CROPPING, INTERCROPPING AND LEGUMES

A reasonable amount of evidence exists about the impact of cover crops usage in agriculture on GHGs. The data available for intercropping is more equivocal and less certain.

For cover crops there is good agreement among studies that cover crops (crops that are planted to improve soil health between harvests) increase soil organic carbon sequestration[31,32,33,34]. For example, Abdalla *et al.* (2019) showed that cover crops (both leguminous and non-leguminous species) increased soil carbon storage[33]. However, there is more variation on the effect of cover crops on the direct emission of GHGs, especially carbon dioxide (CO_2) and N_2O, and further research is needed to increase understanding. A review of cover crop impacts on GHGs reported they could sequester 1 to 1.5 $t.CO_2e/ha/yr$, which is higher than mitigation from transitioning to no-till. The surface albedo change due to cover cropping may mitigate a further 0.12 to 0.46 $t.CO_2e/ha/yr$[35].

Other potentially important considerations are the management of cover crop residues, tillage regime, water status and input, species used, biome and soil type[33,34,31]. Furthermore, short-term legume fallows (for two to three years) can be used to reduce soil carbon losses and reduce pesticide use in following crops, so have the potential to indirectly reduce GHGs via reducing the requirement for pesticide manufacturing[36].

The limited amount of data available for intercropping (cultivating two or more crops on the same field at the same time) show mixed results regarding GHGs.

Whilst the majority of information on cover crops comes from annual cash crops, information on intercropping derives from both agroforestry systems and from annual cash crops. There is some evidence that the benefits of intercropping come from improved nitrogen use efficiency, especially when legumes and non-legumes are mixed[37], and the potential for reduced fertiliser inputs if legumes are used[38]. However more evidence is required across globally distributed sites to draw clear conclusions.

In summary, the use of cover crops and intercropping as a NbS could deliver benefits in terms of climate change mitigation but further research is required to understand best practice to optimise these agricultural methods.

4. CLIMATE CHANGE ADAPTATION POTENTIAL

NbS can be adopted in arable landscapes to increase our resilience to the impacts of climate change (e.g. increased likelihood of flooding events) and help future-proof our agricultural systems. This section outlines some of the key NbS to help deliver adaptation benefits.

4.1. HEDGEROWS

As well as storing organic carbon, soils under hedgerows also promote water infiltration and storing of runoff water, which is important for both mitigating the impacts of flooding and improving water storage in soil in a changing climate[39]. Hedgerows also prevent pollution and soil erosion, intercepting nitrogen from the surface and subsurface water flow, and phosphorus and soil sediment from the surface water flow[17].

Hedgerows may provide landscape connectivity which enables dispersal opportunities for species across the landscape at a local to national level in response to a changing climate, although the effectiveness of these corridors is not yet established[40]. It is important that when planting or restocking hedgerows, there is an aim to diversify the range of species and select hedgerow species and provenances adapted to a wider range of climatic conditions[41] to ensure climatic resilience.

4.2. HERBACEOUS FIELD MARGINS

Similarly to hedgerows, grass margins alongside agricultural crops also prevent pollution and soil erosion[17]. Field margins also allow some species to move within a landscape and find new locations, either locally or as part of larger-scale species migrations[42], potentially enabling biological communities to better adapt to a changing climate.

4.3. AGROFORESTRY

Agroforestry can help to make arable cropping more resilient in the face of climate change, with benefits accruing from the integration of trees and shrubs into the agricultural system. This offers protection against wind and associated soil erosion, water conservation through reduced evapotranspiration, and a beneficial microclimate in the fields[43,44]. Observed microclimate benefits include a reduction of wind speed, more moderate temperatures due to lower radiation intensities and higher air and soil moisture[27]. All of these microclimatic changes can provide benefits for cultivated agricultural crops and have bearings on crop yield and yield stability[27]. Trees alongside watercourses offer similar benefits to herbaceous buffer strips and can also protect watercourses from temperature extremes through shading[45].

5. BIODIVERSITY VALUE

Many NbS are known to enhance and support biodiversity enabling land managers to address biodiversity decline. This section provides examples of NbS that protect and enhance biodiversity in agricultural systems.

5.1. HEDGEROWS

Hedgerows are protected from removal e.g. through the Hedgerow Regulations (1997) in England and Wales, and have become a key target of agri-environmental schemes across the UK due to their importance. Their linear and continuous structure is important for landscape connectivity, particularly for the migration, dispersal and genetic exchange of wild species. Hedges also contribute to the natural landscape character and provide cultural service delivery, including wellbeing[46].

Hedgerows are considered vital for the survival of many farmland plants and animals, especially in intensive agricultural systems[47]. Studies have shown that the majority of the biodiversity on a farm can be conserved by appropriately managing uncultivated habitats such as hedgerows despite their small area relative to productive land[48],[49]. Hedgerow plant species provide important pollen and nectar resources for a substantial proportion of wild pollinator species[50]. A single hedgerow can support high numbers of species of fungi, plants and animals[51,52], depending on key attributes, such as provision of flowers and size. One study recorded 2,070 species of animals, plants and fungi in a single hedgerow in Devon over a two-year period[53].

In England, at least 21 of the 49 Section 41 bird species are associated with hedgerows and for 13 of these hedgerows are a primary habitat. Similarly, as many as 16 out of the 19 birds used by UK government to assess the state of farmland wildlife are associated with hedgerows, with 10 using them as a primary habitat.

Woody species richness has a positive effect on bird species richness[54], and invertebrate numbers[50]. Three times as many movements of woodland birds have been recorded along hedgerows as across open fields[55]. Similarly, butterflies[56], moths[57] and bumblebees[58] preferentially fly along them, while both bats[59] and hazel dormice[60] find gaps in hedgerow networks can limit day to day movements. The maintenance intensity of hedgerows is an important consideration as, intensively managed, low diversity hedgerows lack dormice[61].

One study showed that hedgerow trees may be especially important for enabling macro-moths to move across an agricultural landscape[62]. Wood mouse density is also increased by the presence of hedgerow trees, potentially due to increased seed availability[63]. Hedgerows can be an important source of decaying wood at a landscape scale, which is essential for large numbers of fungi and invertebrates, including many threatened and scarce species[64]. Soil biodiversity is also enhanced by hedge presence in arable landscapes[39].

5.2. FIELD MARGINS

Margins taken out of production at the edge of arable fields are supported under agri-environmental policy for their many proven benefits to biodiversity[65]. For example, grassy field margins host more species and higher numbers of insects, spiders, wild plants, birds and mammals, compared to control cropped field edges. Margins sown with wild flowers or specific varieties of nectar-rich plants for pollinators are particularly beneficial for flower-feeding insects such as bees, butterflies and flies, although the types of insects that benefit depend on the specific plants sown.

Specific conservation-focussed management of arable field margins can also help support scarce and declining farmland birds, such as the turtle dove[66] and are valuable in supporting rare flora such as shepherd's needle[67]. The provision of grass tussocks and beetle banks in field margins also provide year-round habitat for a number of invertebrate species[68]. Vegetated field margins have also been shown to increase pollination services, pest regulation (see next section), nutrient cycling in the soil and off-site soil erosion[69].

5.3. CONSERVATION BIOLOGICAL CONTROL

Conservation biological control, or natural pest control, is the control of agricultural pests, including insects, plant pathogens and weeds, by naturally-occurring organisms in the agricultural ecosystem. Conservation biological control is a central element of Integrated Pest Management (IPM)[70,71] and especially important in organic farming, where it is linked to increased crop production[72], and could be responsible for up to 20% of cereal yields[73].

Conservation biological control can be enhanced through a range of management approaches, with carefully engineered solutions such as combining trap and repellent plants, and using attractant plants or chemicals such as pheromones to bring in natural enemies of pests, being among the most effective[74]. Well-designed flower strips alongside arable fields also enhance natural pest control and can therefore reduce the need for insecticides[75,76], thereby reducing the direct and indirect adverse impacts of pesticides on biodiversity[77,78].

Furthermore, relying on natural pest regulation enhances biodiversity, because it involves increasing the densities of wild species such as birds, insects, bats and spiders. Increasing the diversity and abundance of these species has been shown to increase pest regulation across a range of studies[72]. This can be achieved by diversifying agroecosystems at crop, field, and landscape levels, increasing the number of crop and non-crop plant types across wider areas over time, thereby enhancing floral and habitat diversity.

5.4. AGROFORESTRY

The inclusion of tree rows into agricultural systems can provide habitat akin to well managed hedgerows, with increases in agronomically beneficial species such as spiders and ground carabid beetles in a manner similar to "beetle banks". These species may afford some benefits for pest control within the arable crop[79]. However, non-beneficial fauna can also have an impact, for example lower crop yields linked to slug damage emanating from the tree rows[80].

A wide-ranging review found that the overall impacts were considered positive[81], while a meta-analysis reported increases in natural enemy abundance (+24%) and decreases in arthropod herbivore/pest abundance (−25%)[82]. Agroforestry can also enhance biodiversity through acting as a keystone structure due to the high ecological value they can introduce into modified landscapes and they can also play an important role in facilitating climate change adaptation through the provision of ecological connectivity[83].

6. TRADE-OFFS

The implementation of NbS in agricultural systems needs careful consideration and management to balance the need to maintain agricultural productivity with the objective of reducing environmental degradation and mitigating climate change. This final section explores some of the trade-offs that may be associated with certain NbS.

6.1. YIELDS AND PRODUCTIVITY

6.1.1. HEDGEROWS AND FIELD MARGINS

Hedges deliver multiple ecosystem services (at field and landscape scales), with trade-offs being primarily in terms of taking up areas of potential production land and minor impacts on crops due to shade and water use (in dry conditions). Hedgerows may reduce yield in land adjacent to the hedge, through shading, with arable yields reduced by an average of 29% up to a distance of twice the hedge height away[17].

However, almost certainly these disbenefits are outweighed by positive impacts on cropping including prevention of soil erosion, water retention, provision of habitats and food sources for pollinators and crop pests[15].

One important study has shown that the yield benefits from enhanced pollination and/or natural pest regulation balance out the lost yield when up to 8% of land is taken out of production and managed carefully as flower-rich habitat[84]. Another study has shown that in soft fruit cropping systems (blueberry), flower strips more than pay for themselves in yield increases after four years[85]. However, a recent large meta-analysis of data from 529 sites around the world indicates that the effect is not always found[75].

Flower strips and hedgerows can enhance natural pest regulation and pollination, especially at the field edges near the strips, but they do not consistently lead to yield increases. Yield benefits may take time to accrue and habitat measures must be carefully designed for specific systems to avoid a trade-off.

6.1.2. AGROFORESTRY

Although agroforestry in tropical and dryland systems have been shown to increase crop yields[86], there is limited evidence of these benefits in temperate regions. A study did find increased wheat yields in an agroforestry system relative to wheat in an open field and explained them with a reduction in evapotranspiration rate in the alleys[87]. In some cases though, agroforestry may lead to a decrease in yields. This is particularly the case where arable crops are intercropped with mature trees[88]. However, it is worth noting that reduction in crop yields may be more than compensated for when factoring in both the crop and tree components of the agroforestry system (for example through harvesting fruit), but better models are needed to elucidate the full effects of agroforestry on arable productivity[89]. Furthermore, when intercropped trees are less mature, yield may be improved in some situations[88].

More importantly for the farmer, and depending on the choice of trees, agroforestry can be as, or more, profitable than monoculture systems. Although the farm business becomes more complex, the diversification of income streams brings benefits, alongside wider opportunities for the local economy[90].

7. CONCLUSION

This chapter describes and assesses specific interventions that can enable arable farming to mitigate and adapt to climate change in ways that are beneficial for nature.

There is good evidence to indicate that hedgerows and taking field margins out of production for wildlife benefits are effective NbS in arable landscapes, catering for biodiversity and storing carbon. Agroforestry also has the potential as a NbS to increase carbon sequestration as well as enhancing climate change resilience through services such as providing a better microclimate. Conservation biological control is also considered a NbS that should be pursued because it can reduce the need for pesticide manufacturing (and therefore the associated GHGs), while enhancing biodiversity.

Arable cultivation is inherently a highly modified ecological system that does not traditionally lend itself to supporting nature and therefore many agri-environment interventions, including those to benefit the climate, can involve a reduction of arable activity and such trade-offs must be considered. It is therefore of high importance that the application of NbS in agricultural landscapes are researched further in order to establish both the direct and indirect impacts, positive and negative, of such interventions. Given the current opportunities to shape the re-design of UK farming systems, it is important to note that policies will be required to encourage and incentivise changes to intensive farming practices to deliver NbS at the scale desired – this will require careful design, implementation and crucially, rigorous monitoring once implemented.

CASE STUDY 1: ASSESSING AGRICULTURAL NBS FOR CLIMATE AND NATURE

One attempt to assess agricultural NbS has been undertaken by the Institut du Development Durable et des Relations Internationales (IDDRI) which modelled the application of agroecological practices at the European level to assess some of the potential climate, production, dietary and biodiversity consequences of such a shift at scale[91]. The key finding suggests the shift could secure approaching a 40% reduction in the GHG "footprint" of European farming compared to the 2010 level, before factoring in potential soil carbon sequestration[91]. Concomitant benefits to nature would come from the reductions in pesticides, creation of the "ecological infrastructure" and retention of high value grassland[91]. Crucially, the food produced would provide an adequate, but different, healthy diet for the European population.

Compared to other more ambitious scenarios of "net-zero" agriculture, the 40% GHGs reduction may appear rather modest. Such scenarios tend to rely on "sparing" farmland for uses such as forestry that sequester carbon and can benefit nature, but they need to be tested for their assumptions about the impacts of the required intensification to produce more food from less land. Offshored climate and nature impacts of feed imports would also need to be factored in.

Moving forward the discussion of NbS in the agricultural sector needs a comprehensive analysis of the impacts in terms of food production, dietary changes, off-shored impacts, GHGs and environmental impacts of different scenarios to enable like-for-like comparisons to be made.

BOX 1: HEDGEROWS

Hedges are a NbS that has become part of our cultural landscape. They connect semi-natural habitats in our intensively managed landscapes. They provide habitat, food, shelter and navigation routes for numerous species, reduce wind and water erosion, store carbon in soils and in biomass, increase water uptake and reduce pollution in both water and air.

Image 1: Hedgerows, Great Torrington, Devon © Robert Wolton

CASE STUDY 2: FARMER GUARDIANS OF THE UPPER THAMES INTEGRATED LOCAL DELIVERY ENVIRONMENTAL LAND MANAGEMENT SCHEME (ELMS) TRIAL

This partnership case study sets out a methodology for how farmers and communities can become resilient by working (supported by an adviser) as part of integrated partnerships in shared problem-solving. ELMS has the ability to be the conduit for such an opportunity, where the land is mapped with UK Habitat Mapping, and attributed ecosystem function to habitat type and management, then payments for public goods could underpin sustainable food production which can be invested from multiple sources. This process could be societally transformative, enabling and embedding re-localisation of food supply chains, building dynamic procurement systems underpinned by regenerative farming practice that deliver environmental duties and the potential to solve food inequality.

Aims of the trial:

1. To develop an effective natural capital survey methodology with farmers and partners from which public goods and ecosystem services could flow.
2. To assess the role and cost-benefit of a local adviser who can efficiently bring together different stakeholders to deliver multiple environmental outcomes at a local level.

Key outcomes and recommendations:

- UK Habitat Mapping recognised as the optimum platform for natural capital mapping as it is hierarchical and includes management codes that could be attributed to proxy measures around ecosystem function.
- Adviser provides a single point of contact for funders and landowners to maximise opportunities in natural capital investment from multiple sources.
- Landowners submit a verified natural capital map of their land that contributes to Local Nature Recovery Strategies, to help evidence the delivery of Net Gain and other duties such as flooding, air quality, biodiversity and climate emergencies.
- Government-funded advisers (1,000 nationally) to support and facilitate groups of farmers and communities working together across landscapes and catchments.
- Spatial analysis on the submitted maps can help inform local decisions for natural capital recovery and investment to the local economy from public, private and third sectors.

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FRESHWATER SYSTEMS

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1. KEY POINTS

1. Freshwater ecosystems hold high biodiversity. They will be particularly affected by climate change, with changing rainfall patterns increasing the risk of flooding and drought, and rising water temperatures impacting biodiversity. Along with improved water resource management, creating habitat resilience to climate change is a high priority and requires a "wholescape" approach of linked natural environmental and socio-economic systems from uplands to the sea.
2. Freshwater habitats play a critical role in the carbon cycle through high rates of respiration and sequestration. This is a complex area that requires further research to determine how the mitigation potential can be optimised through NbS. With the correct management, ponds are demonstrated effective carbon sinks, and should be an investment priority as they can be easily implemented across a wide scale in the UK.
3. Planting trees to shade and cool rivers can help to protect biodiversity, and the extension of riparian forests into headwater streams can create thermal refuges and moderate temperature changes.
4. NbS can be combined in a catchment-wide approach to manage flood risk, including tree planting, installation of log structures, creation of temporary storage ponds, removal of flood embankments and re-meandering. The current evidence base indicates solutions are effective, however most research has focused on small catchments and relied on modelling for upscaling. There is a need for consistent, large-scale empirical research in this area.
5. Cost-benefit analyses of the use of NbS to reduce flood risk have shown potential for high net positive returns. Many of these result from complementary ecosystem services rather than avoided costs of flood damage alone. Therefore, project appraisals should consider the multiple ecosystem services provided by NbS.
6. Changing floodplain connectivity results in potentially conflicting impacts, with some ecosystem services being synergistic whilst others conflict, and tree planting at scale may result in displacing other land uses and disturbing existing carbon stocks.
7. As NbS are best and most effectively delivered by local-based partnerships, the role of 'Trusted Intermediaries' is vital to facilitate local support, attract resources, and foster engagement of local communities and facilitate Citizen Science.

2. INTRODUCTION

United Kingdom (UK) freshwater environments support a diverse range of habitats and species with over 40,000 lakes, 500,000 ponds and 400,000 kilometres (km) of rivers, in addition to streams, wetlands and groundwater[1]. Freshwater systems and their associated habitats are already impacted by climate change both directly and in association with other drivers (see Figure 1). They will be increasingly impacted due to their sensitivity to stressors, including increased rainfall, rising temperatures and decreased number of days of lying snow, and because they support a disproportionately high proportion of our biodiversity[2]. While attention has focussed on the direct impact of changes to precipitation patterns and temperature, increased water usage and changes in resource management[3] may also result in widespread impacts which reduce the resilience of freshwater ecosystems to climate change. The result will be far-reaching impacts on biodiversity, socio-ecological systems and the human economy[4]. Therefore, enhancing the resilience of these systems, including response to projected increases in extreme drought[5], is a high priority, yet freshwater systems also offer effective nature-based solutions (NbS) to deal with the challenges of climate change.

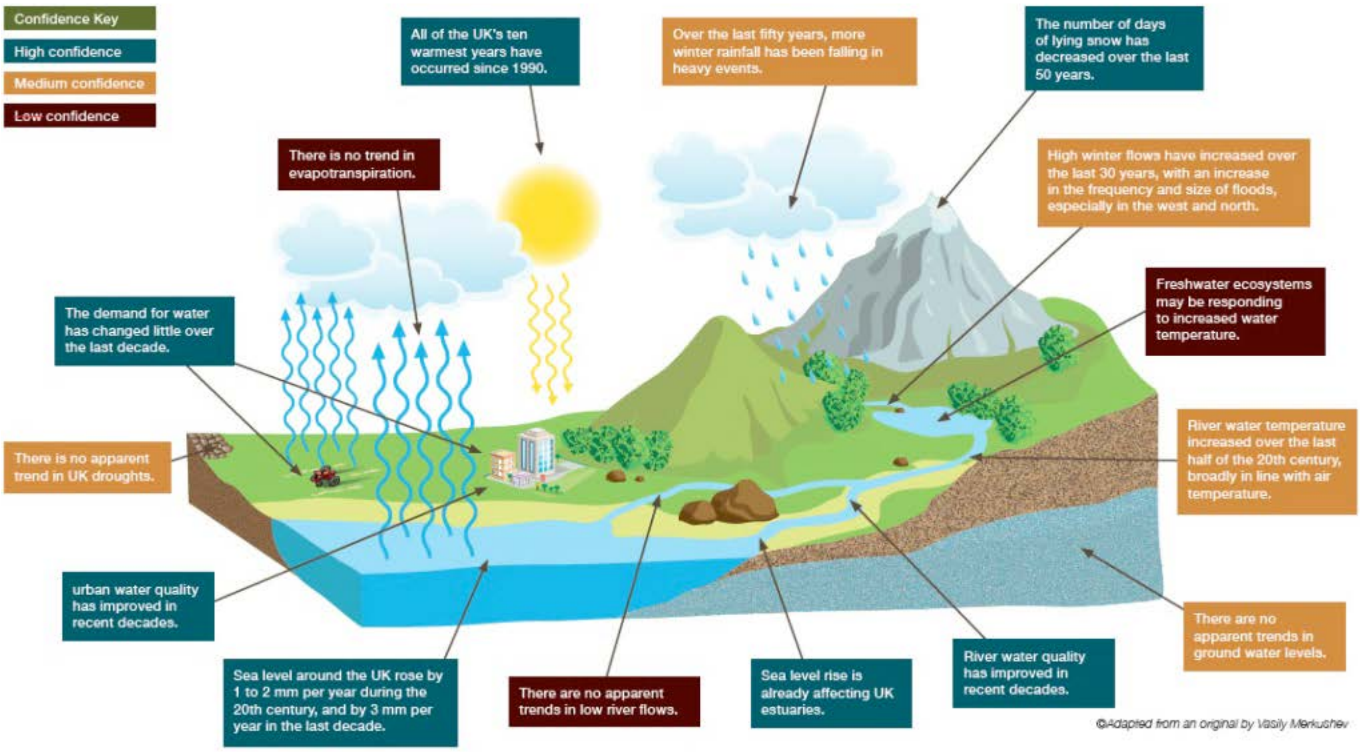

Figure 1. Evidence for changes to freshwater systems resulting from climate change (2016). Adapted from an original by Vasily Merkushev. Reference: LWEC Report Card[4]

A "wholescape" approach that links natural environmental and socio-economic systems from catchment to coast is essential for the management of freshwaters, not only to maintain the ecological connectivity underpinning the wide range of ecosystem services they provide but also their ability to counteract the effects of climate change[6]. This requires the development of governance structures that can deliver an integrated policy framework able to address these issues in freshwater systems, including evaluation of trade-offs between freshwater services, other habitats including coastal and marine, and the needs of diverse stakeholders, including the environment itself.

NbS within freshwater systems can lead to the delivery of synergistic benefits. For example, maintaining wet conditions maintains biodiversity, attracts tourists, protects archaeological artefacts and reduces CO_2 emissions. However, other services potentially conflict; higher water levels may reduce potential flood water storage and increase other greenhouse gas emissions. The identification and resolution of trade-offs between different policy areas and ecosystem services requires verifiable evidence to underpin integrated management[1]. It should be recognised that the most effective solutions may be a combination of NbS and engineering options, rather than one or the other, and it is important to be clear that where NbS are implemented there may be trade-offs, for example large scale tree planting may reduce water resource quantity downstream[7,8].

3. CLIMATE CHANGE MITIGATION POTENTIAL

The mitigation potential of freshwater habitats is a complex area. Despite covering less than 4% of the earth's surface[9,10], evidence suggests that freshwater systems play an important role in the carbon cycle[11,12,13]. Whilst the limited data available indicates large mitigation potential, there is uncertainty. Further research is required to understand the full effects and how these can be optimised through the use of NbS. Uncertainties surround such issues as:

- The interplay between a warming climate and its impact on methane formation;
- The increasing burial of carbon due to land use changes, including intensification of agriculture and the impact of related nutrients[13]; and
- Hydrological impacts leading to runoff-related increases in nutrients and soil erosion.

3.1. PONDS

Limited UK evidence indicates that the carbon burial and storage potential of ponds is promising when appropriate management practices are applied. One study reports an average carbon burial rate in typical lowland UK ponds (over 18-20 years) of 5.21 tonnes of carbon dioxide per hectare per year (t.CO_2/ha/yr) (range 2.90–9.06) once the pond is over 2-3 years old and vegetated[14], but it is unclear how long such rates may be sustained, particularly at the landscape scale with shallow ponds subject to a range of pressures. Mature ponds with higher rates of vegetation are more effective at sequestering carbon.

Recent evidence shows UK pond sediments store relatively high levels of organic carbon, for example a block of sediment one ha in area and 10 centimetre (cm) deep holds between 30 and 60 tonnes of carbon (t.C)[15]. Diverse vegetation appears to be the main factor driving higher storage, whilst surrounding land use is less important, suggesting that ponds could be effective across many different landscapes. There is limited evidence that the precise plant mix may be important, with common pond plants such as species of *Ranunculus* and *Sparganium* beneficial[15]. Newly created ponds may take three years before plant colonisation is sufficient to drive substantial carbon burial[14] suggesting planting can be useful.

Under certain conditions, there is evidence to suggest that ponds can release greenhouse gases (CO_2) and methane) and this potential increases with warming and age. There are multiple examples from boreal/tundra ponds (see Holgerson and Raymond 2016[16]) and more limited examples of disruption to carbon sequestration by ponds dug out in saltmarsh (see Powell et al 2020[17]). Ponds can switch between being sources or sinks of CO_2 rapidly if they dry, although, diverse vegetation appears to reduce this. Therefore, maintaining the effectiveness of ponds over time as carbon sinks and as biodiversity hot spots poses a challenge for optimum site management. Furthermore, it is important to understand the lifespan of ponds, which is potentially limited by changing agricultural practices and natural infilling, and the impact this may have on their long-term potential as NbS.

Although ponds occupy a very small proportion of the landscape compared to other habitats, they are widespread throughout the UK in both rural and urban landscapes. Small ponds are relatively easy to create, and can be fitted in amongst diverse land uses, providing benefits such as slowing rainfall run-off into rivers, as well as being biodiversity hotspots, disproportionately rich in freshwater species, especially rare taxa[18] and with benefits to terrestrial wildlife such as pollinators[19] and farmland birds[20]. Ponds are therefore particularly promising as solution that tackles biodiversity and climate change simultaneously.

Promotion of ponds and other small-scale NbS that deliver natural flood management, pollination and biodiversity gains requires a shift in land management support policies to encourage neighbouring land managers to implement multiple small measures in a joined-up manner so that cumulatively they add up to a wholescape impact.

3.2. RIVERS AND STREAMS

Inland rivers and streams play a significant role in the carbon cycle through moving carbon from the land to the ocean[11], where it can be absorbed, buried in sediments or released back into the atmosphere (see Chapter 7). However, rivers and streams are also a source of carbon[21]. This process is an important part of the carbon cycle which requires further research on how it can be optimised through NbS. Expansion of riparian woodland leading to absorption and storage of more CO_2 from the atmosphere can provide mitigation and is discussed further in Chapter 1.

3.3. LAKES

Research indicates that UK lakes may be both significant sources and sinks within the global carbon cycle[22]. Lakes have significant potential to sequester carbon either derived from terrestrial[12] or aquatic sources, or drawn down from the atmosphere[23], with a recent study finding that globally lakes bury 440 million t.CO_2/yr[13]. which has tripled over the last 100 years. Lakes are also sites of long-term sequestration, less likely to be impacted by infilling, land management strategies or infilling than ponds.

Over time, lowland lakes across Europe have experienced eutrophication, meaning they contain excess nitrogen and phosphorus as a result of land-cover change and agricultural intensification[23].

Research suggests eutrophication has increased the carbon burial potential of lakes [23,24,25], with the highest burial rates being found in small, eutrophic lakes[26]. A study of 90 European lakes, of which 60% were eutrophic, found an average organic carbon accumulation rate of 2.20 t.CO_2/ha/yr, which rose to ~3.67 t.CO_2/ha/yr for lakes that contained over 100 micrograms of phosphorus per litre, with a strong relationship being found between burial rates and phosphorous[23]. Therefore, enhanced carbon burial by lakes may be a positive side-effect of the otherwise negative impacts of eutrophication, which include increased water treatment costs, biodiversity loss, ecological change and loss of amenity value lakes[23,27,28]. However, eutrophication also results in increased emissions of other greenhouse gases (e.g. methane[29]), therefore further research is required to determine whether restoration of lakes to clear water would result in them being a source or sink overall, as well as the impact on other ecosystem services of lakes. It should also be noted that a large proportion of UK lakes, the majority of which are in Scotland, are deep (> several metres), rather than being shallow or lowland in nature.

To a lesser extent than changes in nutrient balances, the net carbon uptake and burial efficiency may also depend on climate[30], the timing and strength of seasons[30] and the carbon source[23]. Increasing depth has a negative impact on the sequestration potential although further research is required to determine why this is [31,23]. Although further research is required, evidence suggests lake sediments may switch between being a carbon source and sink[30] and, given the significance and scale of these fluxes[32,30], understanding this is essential to assessing the ultimate net effect of carbon processing and how this can be optimised through management[12,33].

4. CLIMATE CHANGE ADAPTATION POTENTIAL

The importance of restoring riparian and wetland habitats (see Case Studies 1 and 2) to help adapt to the effects of climate change has been well documented[34], including the International Union for Conservation of Nature (IUCN) National Committee UK (NCUK) River Restoration and Biodiversity Programme[35].

4.1. CHANGING PRECIPITATION PATTERNS AND NATURE-BASED FLOOD RISK REDUCTION

As a response to climate change, it is predicted that patterns of precipitation will continue to change absolutely, seasonally and geographically, alongside increases in the frequency and severity of extreme events[36]. UK Research has mainly focussed on the use of NbS for addressing these changes, often referred to as 'natural flood risk management' (NFM). This includes a variety of measures embedded in a catchment-wide 'wholescape' approach, including:

- Reducing rapid runoff generation in the uplands;
- Reducing flood conveyance along hillslopes and in river channels; and
- Temporarily storing floodwater on the floodplain, in ponds and other receptor areas, including sustainable drainage systems[37].

Several reviews have explored this in detail, as well as assessing confidence in the results[37,38,39], including the Environment Agency (EA)'s Working with Natural Processes (WWNP) Evidence Directory[40]. Alongside traditional engineering, NFM can be utilised to help reduce flood risk and deliver a range of co-benefits[38], for example, land-based NFM can play a significant role in the protection of coastal habitats and fisheries[6]. However, despite growing interest both in policy[41] and practice[40], there is a lack of consistent evidence for their effectiveness. Whilst downstream reductions in flood flows have been predicted in several cases, almost all are from small catchments over short timescales[37] or relied heavily on modelling[38]. In larger catchments, the ability to detect the impact of NFM is complicated by simultaneous catchment-wide responses to land use management changes, as well as environmental variability[42]. Partly as a result of these uncertainties and other socio-economic barriers, uptake at meaningful scales has been constrained. This highlights the need for long-term empirical studies, combined with further evaluation of multiple benefits, and the integration of NFM into standard Flood Scheme Option appraisal policy and processes. To support this, policy changes would be beneficial, including updated business case guidance and the requirement for full assessment of the multiple benefits delivered by NbS[43], as well as reinforcement of policies to ensure no building in the floodplain.

4.1.1. COST-EFFECTIVENESS

The costs of flooding in the UK were estimated to be £340 million per annum in 2016 and are forecast to rise to £428 million with a two degree temperature rise scenario[44]. The total economic damages for England from the 2015-2016 winter floods were estimated to be around £1.6 billion[45]. Flood mitigation services provided by nature can reduce these costs and NFM measures are increasingly proposed as cost-effective ways to assist the provision of flood regulation, especially when considering the additional ecosystem services provided[46]. There is an estimated willingness to pay of £653/household/yr for houses at risk of flooding to avoid intangible flood impacts[47]. In Cambridgeshire, the flood protection benefits for farmers and homeowners from restoring the wetland in terms of avoided damage to crops and property were estimated to be £17,750/yr or £37/ha/yr[48]. Data on wetland restoration show that in some circumstances, costs can outweigh benefits[49]. However, positive returns can be obtained from investment in sites with an average size of 100 ha, located in areas where economic returns are likely to be highest (such as in close proximity to large populations)[49], with benefit-cost ratios between 1.3 and 9[50]. As noted in the Eddleston study (see Case Study 1) and elsewhere, the high positive net present value benefits of NFM are in many instances delivered by the multiple other benefits.

4.2. TREE PLANTING

Widespread woodland creation (by planting or natural colonisation) in the uplands and headwater gathering grounds can help to reduce runoff generation, though direct evidence shows an uncertain overall impact on flood flows[51]. It is however important to avoid planting of peat soils which would not naturally be forested and often required artificial drainage (see Chapters 1 and 3). Increasing tree cover has a small effect on reducing channel peak discharge[51] and influencing fluvial flood peaks[52]. Woodland planted in the floodplain can slow overland flood flows, through increasing surface roughness[51]. Other studies show the importance of woodland, especially old broadleaved trees, in increasing the infiltration of precipitation into groundwater (5-6 times higher than in adjacent grassland), thus reducing the amount contributing to rapid overland flow and surface flooding[53].

Tree planting at the scale at which it would be needed to make an impact on flood risk creates trade-offs as it would displace other land uses[54], including peatlands (see Section 4.2) and agricultural production, as well as produce changes in carbon stocks. However, it can also benefit biodiversity and other ecosystem services[55,56]. Negotiating the challenges that tree planting as a NbS will create with competing land uses will require an overarching policy framework such as illustrated in the Scottish Land Use Strategy pilot in the Scottish Borders[57] and more recently with the Welsh Government's Natural Resources Policy[58], and the Woodland Trust's recommendations[59].

CASE STUDY 1 – USING NATURAL-FLOOD MANAGEMENT MEASURES TO REDUCE FLOOD RISK AND IMPROVE HABITATS AT A CATCHMENT SCALE

Started in 2010, the Eddleston Water project is the Scottish Government's study on the effects of NFM on reducing flood risk and improving habitats at a time of rapid climate change.

Working with 20 farmers, the project has re-meandered three km of river, installed 116 high-flow log structures, created 28 storage ponds and planted over 330,000 native trees. These are designed to provide temporary storage of runoff in channel, floodplain or subsurface stores, thus delaying and reducing downstream flood peaks.

Key findings include:

- Headwater catchments up to 26 km^2 provided with leaky wood dams, on-line ponds and riparian planting show increases in flood peak lag time from 2.6-7.3 hours. The lag time increases with event magnitude.
- The flood peak in the upper catchment has reduced by c.30% post-implementation of measures, whilst the high flow frequency (at a one-year return period) has decreased by 50%. Even the downstream 69 km^2 catchment gauge shows a 29% decrease in high flow frequency.
- Modelling landscape-scale tree planting under different climate change scenarios shows up to 40% reduction in peak flows, and flood peaks delayed by 45 minutes.
- Infiltration of rainfall into soil and groundwater beneath mature broadleaf woodland is between five and six times that under adjacent grazed pasture, which experiences greater surface water runoff.

NFM also provided additional ecosystem services benefits:

- Re-meandering the channel increased the area and diversity of habitats, with overall species richness increasing as habitat diversity increased. Aquatic invertebrates rapidly recolinised the new channels, which also had increased areas of habitat suitable for spawning salmon and parr.

- Using a 100-year appraisal period, the ecosystem services associated with NFM features already implemented is estimated at £4.2 million net present value (NPV) on top of £950,000 flood damages avoided, and at £17.7 million for an additional modelled NFM scenario, on top of £2.85 million flood damages avoided.
- Cost-benefit analysis of the modelled impact of extensive catchment afforestation on peak river flows under different climate change projections also show positive results. Benefits derived from climate regulation, aesthetic appeal, recreation and improved water quality contribute to a high positive NPV.

Figure 2: Eddleston Water Project Natural-Flood Management Measures (left, aerial photo © Tweed Forum; right, log jam © Chris Spray)

References: [60,61,62,55,63]

4.3. RUNOFF ATTENUATION FEATURES AND TEMPORARY STORAGE PONDS

Runoff attenuation features 'slow and filter' surface water runoff in the landscape; for example, placing engineered log structures in headwater stream channels has been shown to potentially decrease flooding downstream[64]. Empirical results from the Eddleston study (see Case study 1)[61] show the impact of in-stream log structures and temporary storage ponds in delaying the rise in peak flood waters for a catchment of at least 25 km[1.] Along with the creation of soil, wood or stone barriers across flow paths, and the removal of river embankments to enable water to spill onto the floodplain, these NbS can be effective for small one in two year events[65] in small catchments[1]. However, there remain issues of how realistic modelling approaches are for upscaling this[66,67] and there is currently limited empirical evidence to support this for greater flood events or across larger catchments[68]. However, research is emerging to show that small-scale micro catchment measurements slowing peak flow reductions can be combined with whole catchment modelling to demonstrate the implications of this at larger catchment scales[61].

4.4. RE-INTRODUCTIONS AND SPECIES MANAGEMENT

The re-introduction of Eurasian Beavers to the UK has the potential to improve habitats and adapt to climate change, particularly by addressing catchment flood risk. Evidence for their effectiveness largely comes from the Scottish[69] and Devon's river Otter[70] studies. The creation of dams and ponds and other beaver activities was shown to attenuate flood flows, reducing peak discharge by 30%, total discharge by 34% and increasing lag times by 29%[71]. Beavers' impact on wetland vegetation is well studied[70,72], with evidence also for reduced sediment, nitrogen and phosphate[71.] In plot trials, mean plant species richness increased by 46%, cumulative number of species by 148% and there were corresponding increases of 71% in heterogeneity[72].

However, the reintroduction of beavers has raised significant issues around trade-offs, with clashes between sectoral views of the damage caused to angling and farming interests, as well as observations that beaver ponds are significant sources of methane and nitrous oxide emissions[73]. Beavers received protected species status in Scotland in May 2019, but between then and 31st December, SNH licenced the shooting of 87 beavers, as well as approving dam removal/ manipulation to prevent serious damage to prime agriculture land[74].

4.5. INCREASING TEMPERATURES AND NATURE-BASED ADAPTATION RESPONSES

Evidence at the UK scale[75] and on the Dee in Scotland[76] show long-term warming trends of river temperature mostly related to increasing air temperature, but at the same time the contribution of snow melt in spring is declining[76]. Water temperature can significantly impact the distribution, health and survival of aquatic wildlife, with species such as salmonids ceasing to feed at temperatures above 20 degrees Celsius (°C) and water temperatures above 30°C possibly being lethal to sensitive species. Given the pace of temperature changes, it is unlikely that freshwater species can adapt to upper temperature limits for survival, feeding and growth through evolution[77,78,79,80]. Hence, it is likely that the long-term distribution of species will be driven by the availability of habitat which is thermally suitable. Summer 2018 saw unusually high air temperatures and low river discharges, with 69% of Scottish rivers reaching temperatures that cause thermal stress to salmon on one or more days[81], on top of which increases in extreme drought are projected in the next few decades[5].

4.5.1. SHADE TREES

The extension of riparian forests into headwater streams can moderate temperature changes, especially in temperature-sensitive zones of the stream network[82]. Modelling has shown that woodland planting would be most effective where channel widths are relatively narrow, the gradient is low (maximising water retention time) and, within the UK, a predominately southerly distribution of bankside trees to maximise shading. Spatio-temporal statistical models of river temperature can help inform management of Scottish salmon rivers, in particular riparian tree planting[83]. Bankside cover as low as 30% can be effective in creating cold water refugia[82]. Empirical evidence shows that tree shade can reduce temperatures in small rivers on average by 2-4°C compared to unshaded streams[84]. Extending riparian tree planting into headwater streams, whilst avoiding deep peat in upland areas is a high priority policy recommendation.

4.5.2. THERMAL REFUGES

River reaches which receive groundwater inputs will be least sensitive to air temperature rise and may allow species to survive heat waves[85]. These thermal refugia are generally >2°C cooler than the surrounding ambient water temperature[86]. They are typically created by riparian or landscape shading, higher altitudes, deep pools, or from the input of groundwater springs or cool water tributary inputs. During periods of heat stress trout and salmon thermoregulate by finding thermal refuges[87,88], hence these areas will have increasing importance as heat waves become more frequent.

Practitioners can use thermal refuges as a NbS by:

1. Ensuring potential thermal refuges are accessible, including prioritising fish passes and weir removals in areas which contain thermal refuges.
2. Protecting thermal refuges from pollution and abstraction.
3. Enhancing thermal refuges to ensure habitat is suitable and offer refuge from predation.

4.5.3. STANDING WATERS

Long-term studies on lake systems have shown significant temperature increases[89] particularly in areas of shallow water during the summer, when flows are low. Whilst further work is required to assess the impact of catchment land use change (e.g. afforestation) on standing waters and this mostly applies to shallow, smaller waters, it is clear that creating and maintaining thermal refuges by, for example selectively increasing depth and introducing shading is an important response to temperature changes.

Actions taken elsewhere in the catchment upstream, such as preventing channels from becoming wider, shallower and warmer, and by controlling bankside erosion and maintaining deep pools will all indirectly assist in managing rising water temperatures in the receiving standing waters themselves by restricting temperature rises in their inflows.

4.6. OTHER AREAS FOR ACTION

Replacing greenhouse gas-emitting fossil fuels with cleaner, renewable energies raises the potential for expansion of run-of-river hydropower schemes, but also of trade-offs with damage to biodiversity and riverine connectivity, notably in Scotland to salmonids, freshwater pearl mussels, bryophytes and other species[90]. Other areas for potential action, noted by the UK's National Adaptation Programme[91], include working towards reducing water leakage and addressing other pressures on water resources caused by behavioural changes in consumption, as well as the expansion into new areas of water-intensive crops.

5. BIODIVERSITY VALUE

In the UK, freshwater habitats occupy a wide environmental gradient from clear, acid, nutrient poor waters in the uplands to more neutral, nutrient rich and biologically diverse systems in the lowlands[92]. Due to their dynamic nature, they support a rich diversity of biological communities, but the isolated nature of some populations makes them particularly vulnerable to climate change and other pressures. Freshwater habitats are essential to the lifecycle of both freshwater specialist species and species which move between fresh water and other adjacent habitats, including the sea. Within the UK, around 4,000 invertebrate species live in freshwater, including around 300 threatened freshwater species[93]. There are 42 native freshwater fish in England of which eight species are of European importance and 15 are included on the UK Biodiversity Plan priority list[93].

Lakes, ponds, rivers and streams are represented in the suite of sites designated as protected areas of local, national and international conservation importance. Some habitats are nationally rare, such as tufa depositing streams, turloughs and marl lakes[94]. Ecological connectivity is often highly important in the functioning of freshwater habitats, both within the habitats themselves and with the wider ecological landscape, where they can form part of broader mosaics of wetland habitat[95], thus reinforcing the need for a 'wholescape' approach to management.

Focusing on small wetlands within an agricultural landscape is very effective for conservation, as they are disproportionately rich in freshwater species, especially rare taxa, and with benefits to terrestrial wildlife such as pollinators and farmland birds. The importance of including runoff and flood storage ponds as NFM measures to reduce flood risk can be key to significant gains in freshwater plant biodiversity at both the site and whole catchment scale. The extent to which adding such adaptation measures to the full range of different small habitat patches across agricultural landscapes has been very effectively demonstrated[96], reinforcing the importance of taking an integrated catchment approach within the wholescape framework to NbS. This aligns both with the earlier policy recommendation for support of small-scale NbS connected across the catchment landscape and, at the international scale, with the UK being a signatory to the Ramsar Convention which requires the wise use of all wetlands.

Water birds are very well monitored and changes in the populations of many wetland species can be closely linked to hydrological changes. The breeding water and wetland bird indicator for the UK fell by 6% between 1975 and 2017[97]. Where increases in wetland bird populations have been seen, it is in those species associated with areas of new reedbeds, flooded gravel pits and other restoration habitats, suggesting that this may represent excellent opportunities for NbS. There is also continuing concern about the general status of aquatic macroinvertebrates, including the impacts of agricultural run-off, as well as the localised impacts of pollution events. However, the UK State of Nature Report reports some recovery[97], of which improvements in water quality, hydrological management to restore rivers, and the creation of specific local-scale habitat features are likely to have played an important role, enhancing the potential for biodiversity gains from NbS. As demonstrated in Case Study 2 below, there is also a need to link freshwater policies to those covering estuarine, coastal and inshore environments (see Chapter 7).

CASE STUDY 2 – HABITAT CREATION AND NATURAL FLOOD MANAGEMENT: WWT STEART MARSHES

The EA partnered with the Wildfowl & Wetland Trust (WWT) to design and create an extensive new wetland complex encompassing 450 ha of freshwater, brackish and saline habitats on the Steart peninsula near Bridgwater, Somerset. The project was completed in 2014, creating 300 ha of intertidal habitat, 75 ha of grazing marsh, 39 ponds and scrapes, and 5.5 km of new watercourses controlled by 20 water-level structures, plus the planting of almost 50,000 native trees and wetland plants.

Both the intertidal and freshwater wetlands provide natural flood management. The freshwater ditch network was redesigned to reduce local flood risk and, in doing so, the freshwater Stockland Marshes were created that attenuate and store floodwaters. Sensitive grazing and water-level management has led to the biodiversity value increasing with many species of wintering waterfowl now found in nationally important numbers. The recent colonisation of avocet has led to the establishment of the largest breeding population within the south-west UK and in 2020 black-winged stilt bred and successfully reared three chicks. A recent Odonata survey indicates the site now exceeds national thresholds for some species.

The 300 ha of intertidal habitat were designed to compensate for saltmarsh habitat lost through coastal squeeze, and the colonisation of saltmarsh plants and accretion of silt has been rapid. WWT has actively engaged with the scientific community to encourage research at the site. The research being conducted at the site may provide a model for evaluating the multiple benefits of future coastal realignment schemes and advance understanding in the blue carbon value of saltmarsh creation. Additionally, an Ecosystem Service Assessment has determined a significant overall monetary benefit of the scheme.

The main findings are:

- 300 ha of created intertidal habitat comprising of 250 ha from an open breach and 50 ha through a regulated tidal exchange.
- An estimated accumulation rate of 92 t.CO_2/ha/yr has been calculated.
- 17 saltmarsh species including sea lavender, sea plantain and sea arrowgrass have colonised within five years.
- Wintering populations of avocet, black-tailed godwit, dunlin, greenshank, lapwing, little egret, redshank, shelduck, shoveler, teal, pochard and sanderling exceed nationally important thresholds.
- Visitor numbers have increased from approximately 11,000 in 2010 to >49,792 in 2019.
- A net annual ecosystem service benefit of between £491,155 to £913,752 has been estimated.

WWT Steart Marshes became an exemplar in working with natural processes on a landscape scale, creating extensive wetland habitat, reducing flood risk to local communities, storing carbon and providing an amenity for thousands of visitors to experience the multiple benefits of wetlands.

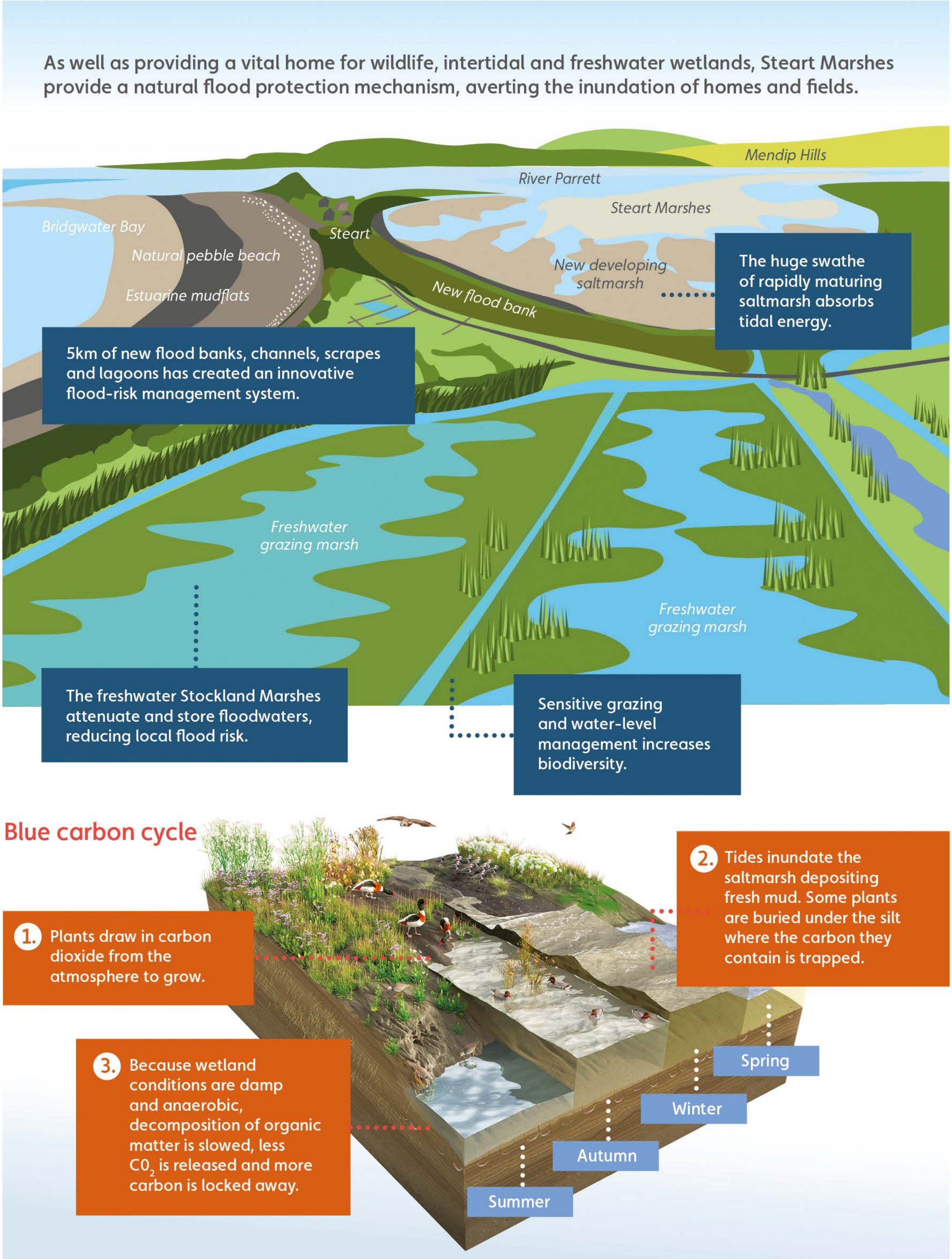

Figure 3: WWT Steart Marshes Habitat Creation and Natural Flood Management © WWT

References: [98,99,100,101,102,103]

6. HUMAN WELLBEING AND SOCIO-ECONOMIC VALUE

As well as flood prevention, freshwater habitats provide socio-economic benefits including provision of water, improvement in water quality, recreation and education. In a UK based survey, the main benefits people received from visiting freshwater blue space were psychological, social interaction and exercise[104], and the presence of freshwater bodies in neighbourhoods has been associated with better mental health[105].

Studies of NbS catchment interventions provide extensive evidence for the benefits to society they provide[73]. Whilst some lead to the delivery of synergistic benefits, including maintaining biodiversity, attracting tourists and protecting archaeological artefacts, other services potentially conflict; higher water levels may reduce potential flood water storage and increases in methane and nitrous oxide emissions may enhance atmospheric warming. Therefore, careful consideration of trade-offs is required. In this context, policy recommendations need not only to reinforce planning presumptions against development on current and historic floodplains, but also to promote active consideration of 'retreat' from locations at risk of flooding now or under future climate scenarios, with the land re-purposed for appropriate NbS to deliver flood risk reduction and biodiversity gain.

7. ASSESSMENT OF THE QUALITY OF THE EVIDENCE

The effectiveness of NbS at addressing climate change and providing biodiversity benefits is variable between measures and across scale[106]. It is an area where further research and evaluation is needed.

The EA Evidence Directory[40] classed Floodplain restoration measures as low/medium confidence (reflecting a lack of empirical data and small scale); the planting of catchment woodland as high/medium confidence (but recognising time lags for some of this impact) and Landscape storage as medium confidence (and, as adaptation measures relying on ongoing maintenance). Some measures, such as in-channel wood structures or beaver activity can produce quick direct responses; others such as tree planting may have extended time lags. The evidence for effectiveness of the whole suite of NbS measures to reduce flood risk is high for small catchments, for small scale flood events and over short time periods[38,37]. However, upscaling the results produces much greater uncertainty and relies heavily on modelling[37]. In this context, empirical proof of significant delays in time to peak floods from BACI studies in the Eddleston is encouraging[60], as is work to extend this through detailed model development to larger catchments[61].

At larger scales, influences acting across the wholescape such as differences in land use and land management, and in geology and connectivity to groundwater will further complicate simple cause and effect of NbS to influence temperature and hydrology[107,108].

BOX 1: THE IMPORTANCE OF TRUSTED INTERMEDIARIES IN FACILITATING DELIVERY OF NATURE-BASED SOLUTIONS

As NbS are best and most effectively delivered by local-based partnerships, experience shows the role of 'Trusted Intermediaries' is key to facilitating local support and getting the buy in of affected communities. They are also able to attract resources, including new sources of funding for delivery of multiple benefits, and support from local business and landowners[43], as well as fostering engagement by local communities and facilitating potential enhancements through Citizen Science. Whilst there is no specific mechanism or single governance structure for multi-level collaboration, organisations such as Tweed Forum and Westcountry Rivers Trust have demonstrated the advantages for delivery of NbS by their positioning between community, business and government interests[57,109]. This approach is seen as key to successful NbS implementation, especially in comparison to traditional, top-down infrastructure solutions and approaches to climate change adaptation.

There is a policy need to establish a requirement for Partnership working at a catchment/landscape scale (as e.g. legally required in the Flood Risk Management (Scotland) Act 2009); and for active support for the maintenance of catchment/landscape-based organisations acting as Trusted Intermediaries to deliver NbS.

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COASTAL AND MARINE SYSTEMS

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1. KEY POINTS

1. Marine and coastal ecosystems can contain and absorb significant amounts of carbon, especially given the large area some habitats occupy. There is significant restoration potential for habitats such as seagrass and saltmarsh, given the historic loss of these habitats through pollution and development.
2. Saltmarsh and seagrass are important carbon sinks which can be managed or restored through NbS as part of a national carbon budget. Continental shelf sediments, while having lower sequestration rates, show great potential for carbon sequestration due to covering a large area, but more uncertainties exist in the data. Kelp and other seaweeds are likely to have a role in carbon sequestration, however research into this role is still in its infancy.
   - Saltmarsh: typical UK sequestration rate of 4.40–5.50 $t.CO_2$/ha/yr
   - Seagrass: average sequestration rate of 5.06 ± 1.39 $t.CO_2$/ha/yr (specific UK figures not available)
   - Continental shelf sediments: sequestration rate of 0.06 $t.CO_2$/ha/yr
   - Kelp and other seaweeds: initial estimated sequestration rate of 1.47 $t.CO_2$/ha/yr
3. Sequestration rates are calculated differently than in terrestrial habitats, so direct comparison to terrestrial NbS in terms of climate change mitigation is difficult.
4. Marine fauna and flora play a large role in ocean carbon cycles and will influence the carbon flux in and out of oceans. Quantifying the direct role of fauna, and indirectly of fisheries, on carbon cycles is uncertain but is an area for further research.
5. As well as providing climate change mitigation services, coastal ecosystems provide protection from storm waves and alleviate coastal flooding. The potential for saltmarsh creation when addressing coastal defence issues is high. Coastal ecosystems also have high biodiversity, contribute to ecosystem services, especially as nursery grounds for fish, and provide human wellbeing benefits. Therefore, investment in NbS that restore or protect coastal environment is an effective mechanism of achieving a range of co-benefits with few trade-offs.
6. Protecting and enhancing NbS in marine and coastal habitats requires consideration of fisheries regulations, particularly gear types which disturb the substrate, as well as effective management of marine protected areas for vulnerable habitats and dedicated restoration of habitats (saltmarsh and seagrass especially).

2. INTRODUCTION

The oceans absorb around 30% of anthropogenically produced carbon globally, as well as converting between 50-70% of carbon dioxide (CO_2) into oxygen via algal photosynthesis[1,2,3]. United Kingdom (UK) waters (not including overseas territories) are ~3.5 times greater in area than the land mass[4], meaning NbS in the ocean could play a very significant role as a carbon sink in the UK's carbon budget. This chapter reviews the carbon sequestration potential of marine habitats (often referred to as Blue Carbon), alongside the benefits to adaptation and biodiversity that they bring. It considers threats and appropriate management measures to ensure these benefits are maintained and maximised in the future.

3. CLIMATE CHANGE MITIGATION POTENTIAL

Carbon sequestration in marine systems is usually calculated differently to terrestrial systems, making direct comparisons between habitats difficult. Within marine systems, sequestration is calculated from the rate at which carbon is buried in sediments[5], whereas biomass increases or direct flux measurement are important in terrestrial systems such as forests[6]. The assumption that non-buried organic matter is eaten or decomposed and respired is highly possible, given the high consumer to producer biomass ratio in marine systems[7] but more work is needed to adequately compare marine and terrestrial systems.

3.1. SEAGRASS AND SALTMARSH

3.1.1. OVERVIEW

Seagrass and saltmarsh are well established marine habitats for carbon sequestration. Currently their geographical extent is limited, and reduced from historic levels, but restoration is possible. However, restored habitats may take time to achieve the same carbon sequestration benefits as established areas.

3.1.2. DETAIL

The capacity of seagrasses to both store and sequester carbon is well established, however, the extent of storage and sequestration is highly variable, related to environmental conditions and life history differences between species[8]. A global study of carbon storage in seagrass sediments over the first one metre of depth finds carbon stocks to vary from 23 to 352 tonnes of carbon per hectare (t.C/ha)[9], with values from the UK falling approximately within the ranges 98 to 380 t.C/ha[10]. The sequestration rate of this carbon also varies, but data and understanding are much more limited. On average 5.06 ± 1.39 t.CO_2/ha/year (yr) (mean ± standard error, range = 1.65–6.97) is stored. The large range reflects environmental and species differences[11].

The extent of seagrass in the UK has recently been estimated at 8,493 ha[12]. There is considerable potential to restore recently lost seagrass (see Case Study 2), with estimates showing that existing seagrass beds have declined by up to 50% in the last 25 years[13] and potentially up to 92% of historic seagrass has been lost in the UK[12]. Although there are no UK values for restored seagrass beds at present, lower sequestration rates of 1.32 t.CO_2/ha/yr were recorded in newly restored meadows of common eelgrass *(Zostera marina)* in Chesapeake Bay, United States of America (US)[14]. A high proportion of the carbon stored in seagrass meadows is thought to have originated outside the marine system (e.g. transported by rivers), reflecting the high capacity of these systems to trap particles from terrestrial and coastal ecosystems. This is particularly the case for common eelgrass (>50%)[9]. The long-term storage of carbon is highly stable, possibly remaining intact for many thousands of years, however human disturbance can destabilise this storage and release greenhouse gasses[15]. Costs of restoration from projects around the world are estimated at ~ $100,000/ha (~ £70,000/ha)[16].

Saltmarshes have been identified as important coastal NbS[17,18], due to their ability to sequester more carbon per unit area than many other coastal habitats. Sequestration rates in UK saltmarsh range from 2.35 to 8.07 t.CO_2/ha/yr, with typical figures around 4.40–5.50 t.CO_2/ha/yr[19]. Saltmarsh habitats are often under-represented in carbon budgets due to their lower total area compared to habitats such as woodland or grassland (estimates at ~ 46,000 ha[20]) but knowledge of their importance as carbon sources and sinks is rapidly expanding[18]. Saltmarshes provide an ideal carbon store, with typically high plant productivity, slow organic deposition in anaerobic sediments[21], and a low energy environment which traps a lot of organic matter[22].

Newly restored areas, often created through managed realignment projects (see Section 4), have carbon sequestration rates of up to 3.81 t.CO_2/ha/yr during the first 20 years, slowing to a steady rate of around 2.38 t.CO_2/ha/yr thereafter[23]. This is lower than typical rates from natural habitats, likely due to different community composition of restored systems[24], however total carbon storage at around 65-70 t.C/ha of both restored and natural saltmarshes is assumed to be equivalent after approximately 100 years[23]. There is large potential for future saltmarsh creation. Over 3000 ha has been created in the UK through managed realignment between 1990 and 2015[25], although it is noted that this potential is more restricted in Scotland[26]. Shoreline Management Plans, which set the strategic policy direction for coastal management taking into consideration the risks, set a target of 6,200 ha of saltmarsh by 2030 within England[27]. The average rate of habitat creation between 2000 and 2016 has been around 130 ha per year and would need to triple to meet this target[27] (see Case Study 3 for further detail).

The cost of restoration is relatively high but can be cost-effective when considering climate adaptation benefits of reduced coastal protection costs (see Section 4). The Environment Agency generally works to a guideline figure of £10,000 /ha (2006 price levels). However, the costs can run to over twice this figure, particularly when significant engineering is required[25], with figures of $67,000 /ha (~ £50,000 /ha) reported from projects occurring worldwide[28].

3.2. MARINE SEDIMENTS

3.2.1. OVERVIEW

Sediments including sand and mud trap organic matter, and comprise the majority of the seabed, both in UK waters and worldwide. Vegetated habitats growing in sediments, such as seagrass, sequester considerably more carbon per unit area than non-vegetated sediments, however, all sediments will play a role[35]. There is a growing and established evidence base that continental shelf sediments sequester and store high quantities of carbon. While this rate per unit area is significantly lower than vegetated coastal habitat such as seagrass or saltmarsh, the geographical extent of these habitats is very large, making them an important carbon sink.

3.2.2. DETAIL

Continental shelf sediments cover approximately 9% of the UK Exclusive Economic Zone waters[29], the equivalent of seven million ha, which is over 130 times greater an area than seagrass and saltmarsh combined. There is growing consensus that shelf sediments are an important carbon store[30,31,32,33]. For example, it is suggested shelf sediments currently store 205 million tonnes of carbon and can sequester 388,667 t.CO_2/yr, or 0.06 t.CO_2/ha/yr[29]. While this is lower per unit area than saltmarsh and seagrass, it is in total a far greater amount of carbon (Luisetti et al. 2019 report 135,667 t.CO_2/yr from saltmarsh and 9,167 t.CO_2/yr from seagrass[29]). However, significant evidence gaps remain in understanding the full CO_2 storage and sequestration services provided by these continental shelf carbon sink habitats, especially sedimentation rates and release through seabed disturbance such as trawling. More research is required to improve their role in contributing to carbon sequestration[34].

3.3. MACROALGAE

3.3.1. OVERVIEW

There is growing evidence on the importance of macroalgae in sequestering carbon, although at present, the magnitude of the effect is hard to evaluate.

3.3.2. DETAIL

Kelp, likely the most important algae in the carbon cycle, is estimated to cover around 200,000 ha in Scotland (the only UK location where habitat extent has been calculated)[35]. Given its high prevalence in Scottish waters including sea lochs, and the lack of suitable substrate for kelp growth around much of south-eastern England, it is unlikely that the total amount would exceed 400,000 ha throughout UK waters, although it is suggested there is scope for restoration to two million ha (including waters in the Republic of Ireland)[36]. The cost of restoration is largely unknown.

Kelp is highly productive and has a rapid growth rate. Most kelp growth is eaten by grazers, and ultimately turned back into CO_2 through respiration. However, new evidence suggests that around 5% of kelp could be sequestered and stored in marine sediments[37,38,39,40,41,42,43]. Based on productivity figures for Scottish kelp beds[35], this could equate to 1.47 t.CO_2/ha/yr in UK waters. However, there is great uncertainty in this estimate.

Data for kelp are more developed than for other macroalgae communities including intertidal algae. Kelp also shows faster growth than many other algal species. It is likely that other macroalgae contribute further to these figures, but as indicated above, there is already considerable uncertainty in the data. Nevertheless, research into the fate of macroalgal carbon is an important area for future research, and marine algae has potential to be considered as a NbS.

3.4. ROLE OF MARINE FAUNA

3.4.1. OVERVIEW

There is emerging evidence that carbon cycling can be greatly affected by marine fauna, and that fishing may have detrimental effects on the carbon budget. While there is low certainty and the extent has not been quantified, it could have large effects due to the area and volume of habitat covered.

3.4.2. DETAIL

Marine fauna, especially fish, make up around 80% of marine biomass[7]. The population sizes of even sustainable fish stocks are typically only 30% of natural levels[44], so any effect of fishing on faunal driven natural carbon cycles is potentially large. Fauna influence carbon cycles in three ways. Firstly, direct respiration produces CO_2, and larger total biomass of animals which could be caused through removal of predators (typically commercially fished species), are likely to increase overall respiration rates[45]. Secondly, fish excrete carbon in various forms, which can sink into the deep ocean. This includes carbon-rich faeces[46] and gut carbonates[47]. Fish that vertically migrate can efficiently transfer carbon from surface to depths through both respiration[48] and food webs[49]. Thirdly, fauna can influence nutrient cycles and affect phytoplankton growth through transporting nutrients from depth to surface layers[50,51,52].

At a worldwide scale, phytoplankton fix between 128 and 138 billion tonnes of carbon per year[1], accounting for 50 to 70% of photosynthesis[2]. Of this carbon fixed by photosynthesis, around 1 to 1.7% is maintained in a fixed state (sequestered) by biological and microbial carbon pumps[53]. As such, while the evidence is currently relatively sparse, and the magnitude of the effect is uncertain, there is a potential that recovery of fish and marine mammal stocks (ideally well above maximum sustainable yield[1] values) will also have potentially large net benefits to carbon sequestration in coastal and open waters[45,44].

[1] The maximum level at which a natural resource can be routinely exploited without long-term depletion.

3.5. LESS ESTABLISHED MITIGATION HABITATS

There is considerable uncertainty in the role of many habitat types, including biogenic reefs and molluscan shellfish formation as a carbon source or sink[2,54]. However, in the UK (specifically Scotland) it has been suggested that processes such as oyster reef formation will contribute little to sequestration overall[35]. Maerl beds and cold-water coral reefs also store carbon (0.5 million tonnes of inorganic carbon in Scottish waters), where the majority of these habitats are found in the UK[35]. However, the sequestration rate is low as they are slow growing, but they do act as a storage mechanism for carbon over geological timeframes.

3.6. ADDITIONS TO THE CARBON BUDGET FROM MARINE ECOSYSTEMS

Recent research has also investigated production of methane and nitrogen oxides by coastal habitats. The research is still developing and does not provide a clear picture for the UK, however, methane production by coastal ecosystems is likely to occur at low rates but could be important given that methane has a 25 times higher global warming potential than CO_2. Typically, seagrass has the lowest rate at $1.5*10^{-6}$ t.C/ha/yr and saltmarsh around four times higher at $6*10^{-6}$ t.C/ha/yr [55]. These values are several orders of magnitude lower than the sequestration rates of the habitats.

4. CLIMATE CHANGE ADAPTATION POTENTIAL

Coastal habitats, including seagrass and kelp, play an important role in protecting the coast from storm damage, for example, by reducing wave action on coastlines. In the US, the provision of coastal protection by marine habitats were estimated to be between two and five times more cost-effective at lowering wave heights and increasing water depths compared to engineered structures across 52 coastal defence projects[56], and in West Sussex, UK, natural capital associated with coastal protection from restoring kelp forests were estimated to have a value of over £1.2 million[57]. There is a strong synergy between mitigation and adaptation, with restoration or protection of habitats such as seagrass or kelp (as opposed to bar sediment or algal turfs) enhancing both climate change mitigation and adaptation. Saltmarsh provides the greatest adaptation potential to climate change, and as such forms the focus of this section.

Saltmarshes contribute to coastal protection through dissipation of wave energy. Field monitoring has shown wave energy dissipation over a saltmarsh as significantly higher (at an average of 82%) than over the adjacent, seaward sand flat (average 29%)[58]. In experiments, generated storm surge wave heights have been shown to be reduced by 12 – 20%, with 60% of this reduction being attributable to the presence of saltmarsh vegetation[59]. Saltmarshes also store floodwaters and thus reduce peak water depths during storm surges, although little data exist to quantify these benefits[60]. Managed realignment (the (re-)creation of saltmarsh between old, seaward defence lines and new defences to landward) is a strategy to protect areas of the coast under risk from rising sea levels. This normally involves allowing sea defences to be breached in certain areas[61]. This newly created habitat also provides the climate mitigation benefits described above. However, the amount of managed realignment currently occurring is well below recommendations in Shoreline Management Plans[62] (see Case Study 3).

In 2015, it was found that the one-off high costs of a five-fold increase in managed realignment (approximately £50,000) are offset by saved flood spending, reduced damage risks and ecosystem services values, resulting in a benefit-cost ratio of

1.4[63]. In addition, the Environment Agency's 450 ha Medmerry Managed Realignment Scheme has saved on recurring coastal protection expenditure, which averaged £300,000 per year, along a formally intact two kilometre shingled beach and it is likely to have helped avoid large damages during the 2013/14 winter storms[63]. The assessed benefits are calculated at £90 million compared to the project cost of £28 million[63].

5. BIODIVERSITY VALUE

Marine habitats which increase structural complexity of the seabed are normally considered highly biodiverse habitats with good evidence that saltmarsh, seagrass and macroalgae will result in enhanced biodiversity compared to bare sediment and algal turf communities[64,65]. Therefore, through careful management or restoration of habitats, the climate mitigation, climate adaptation and biodiversity benefits are enhanced. Seagrasses are habitats for ecologically and economically important species such as scallops, shrimps, crabs and juvenile fish, providing both refuge from predators and food sources[66]. Seagrass is also a necessary habitat for flagship conservation species such as UK seahorse species[67]. Kelp provides important nursery grounds for many commercial fish and shellfish, as well as habitat for lobsters and edible crabs[57,68]. Saltmarshes provide habitat for species that are important for tourism, recreation, education and research and due to their complex plant structure, provide protection and shelter for the increased growth and survival of young fishes, shrimp and shellfish[69]. Bird biodiversity is also enhanced, even on newly created saltmarsh[70]. Habitat services (genetic and nursery services) provided by coastal systems and coastal wetlands have been valued at $375 and $17,138 ha/yr respectively (2007 prices levels)[71].

6. HUMAN WELL-BEING VALUE

There is considerable evidence of the well-being effects of the sea and beaches[72], and habitats such as rocky shores have been shown to be important areas for relaxation and recreation as a result of their biodiversity[73]. Recent analysis of the role of seagrass meadows as social-ecological systems indicates that they help promote well-being through environmental amelioration, fisheries and recreational value[74]. While some habitats, such as saltmarsh, provide important habitats for animals such as birds, which may further contribute to well-being for specific groups, there are few direct links to well-being largely due to lack of public awareness regarding these habitats[75].

7. THREATS AND MANAGEMENT

Threats to non-intertidal marine systems mainly comprise harmful fishing practices, climate change, other development activities and pollution[76]. Poor practices in anchoring and mooring of boats can also harm seagrass beds. Climate change can affect growth and recruitment of some species of UK kelp and affect the carbon dynamics and other ecosystem services, such as fish stocks and changes in the species composition of fisheries catches[77,78]. Climate change can also facilitate the successful establishment and spread of non-native species and change community composition of habitats[79]. Fishing can directly change macrofaunal communities[80], but the main effect of fishing in coastal habitats is through habitat damage from fishing gears[81]. Trawling and other activities such as marine renewable developments, infrastructure installation, and oil & gas exploration and decommissioning can disturb sediment (such as coastal shelf sediment) which may affect stored carbon rates (see Section 3). Pollution, especially that of nitrates and phosphates, can create eutrophication processes which can degrade habitats that rely on photosynthesis such as seagrass beds[82]. Many marine systems actively recover if pressures or threats are removed, but for some, particularly seagrass and saltmarsh, active restoration will be needed to realise their full potential as NbS. Policy measures to reduce greenhouse gas emissions, reduce fishing or prevent damaging fishing gear in sensitive habitats, prevent nutrients entering coastal waters (i .e. through better land-use management) and create effective marine protected areas around key habitats (with management measures to prevent further disturbance to the habitats) will help maintain these habitats as climate mitigation, adaptation and highly biodiverse areas.

Coastal ecosystems such as saltmarsh, while providing adaptation benefits from reducing erosion caused by rising seas and increased storms, are also, themselves, affected by rising seas, as well as additional pressures such as overgrazing. Coastal development also plays a large role, either directly on reclaimed habitat or through altered sediment budgets, causing potential retreat of saltmarshes[83,84,85]. There are considerable differences in the magnitude of saltmarsh retreat[29,86 ,87]. At present, newly created saltmarsh through managed realignment is not thought to keep up with loss of habitat[25], and sequestration rates from new habitat are likely lower than those from existing saltmarsh (see Section 3.1). Policy developments, investment and management measures to reduce the use of hard coastal defences and increase managed realignment will prevent some degradation of saltmarshes through sedimentation changes as well as creating new habitat.

CASE STUDY 1 – NORTH DEVON PIONEER

In the North Devon Marine Pioneer (NDMP), a natural capital approach was used to assess the role that marine habitats have in the balance and maintenance of the chemical composition of the atmosphere and the oceans by marine living organisms[88]. The Pioneer constructed a Natural Capital Asset Register to demonstrate the potential flows and location of habitats that support a healthy climate. Saltmarsh, intertidal reef communities (with algae assemblages) and shallow subtidal (infralittoral) reef (kelp) communities provide the greatest contribution to carbon sequestration within NDMP with estimates of 20.53, 16.50 and 228.07 t.CO_2/yr respectively, based on an assumption that there are no pressure constraints on the ecological functions of these habitats[89]. As noted above in the macroalgae section, algal estimates are subject to considerable uncertainty.

The estimate for contribution of offshore subtidal sediments was not included in this calculation, but potentially could add an additional 43,000 t.C/yr due to the large extents that these habitats cover. A Risk Register was developed to determine if current management of the marine habitats was underpinning the benefits of a healthy climate[90]. Current marine management through Marine Protected Areas, land and fisheries management are not sufficient to reverse decline in the degraded saltmarsh or reef habitats, leading to an 'amber' risk of loss of the role these habitats have in supporting a healthy climate. A conclusion of this case study is that NbS must go beyond current efforts and enable restoration and repair of essential marine habitats[90].

CASE STUDY 2 – SEAGRASS RESTORATION IN WEST WALES

In many parts of the world marine restoration is an active part of the tool kit available to marine and coastal conservation managers. For example, in the Chesapeake Bay in the US after decades of fish declines, increasingly polluted waterways and large-scale habitat destruction a basin wide programme to reverse those declines was put in place. Over a 30-year period this has resulted in the restoration of over 1,000 ha of seagrass (initially sequestering around 1,320 $t.CO_2$/yr, but with potential for ~5,500 $t.CO_2$/yr when habitats mature)[91]. In the UK until recently habitat restoration had not been considered a viable means of creating marine ecosystem recovery. Following four years of research and development work by Swansea University and Project Seagrass, the UK's biggest ever marine restoration project was launched in Dale in West Wales as a collaboration with World Wildlife Fund and Sky Ocean Rescue with the aim of restoring two ha of seagrass. The techniques used built on those successfully employed in Chesapeake Bay[92]. One million seeds are being planted using lines of small hessian bags in order to overcome the high tidal currents, abundance of seed predators and sediment stability. Due to the large-scale historic loss of seagrass in the UK and North Atlantic area there remains huge opportunities to restore these once abundant meadows. Recent studies have revealed that UK seagrass meadows may have lost up to 92% of their historic distribution[12], this equates to thousands of hectares of potential future restoration areas and therefore 100s of thousands of tonnes of potential future carbon sequestration and storage. Our ability to conduct such restoration relies on reducing the per hectare costs of these activities through the design of methods and equipment able to increase the automation of key aspects of this work.

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Seeds
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CASE STUDY 3 – MANAGED REALIGNMENT IN ENGLAND

In the UK, managed realignment has been implemented to restore or create intertidal habitat, mostly to compensate for the loss of saltmarsh and/or mudflats. This has been a preferred coastal management approach for providing multiple benefits, such as sustainable flood and erosion risk management in light of climate change and loss of other ecosystem services[61]. Most often, managed realignment restores tidal inflow into embanked land through planned breaching of coastal defences or installation of sluices (called regulated tidal exchange in the UK). Shoreline Management Plans in England envisage managed realignment projects creating over 6,200 ha of habitat by 2030 and 11,500 ha by 2060[27]. The 69 managed realignment projects implemented in the UK (from early 1990s to date) are potentially creating about 2,600 ha of habitat (Figure 1). If the average rate of habitat creation between 2005 and 2018 (150 ha/yr) is unchanged, 4,500 ha would be created by 2030. This rate would need to double between 2018 and 2030 for the 6,200 ha vision to be realised.

Very few studies quantify the carbon accumulation in managed realignment sites in the UK[23]. A crude assessment of the carbon stock of existing sites can be made considering the age of the sites, the average carbon sequestration rates estimated[23] (up to 3.81 t.CO_2/ha/yr during the first 20 years and 2.38 t.CO_2/ha/yr thereafter) and the arbitrary assumption that saltmarshes occupy half of the site area. The 2,600 ha of existing managed realignment sites would have sequestered roughly 102,667 t.CO_2 by 2030. Rather than comparing to natural saltmarshes, it would be more pertinent to assess gained benefits in relation to the type of habitats that were substituted, which may include former farmland, freshwater habitat and conversion of intertidal habitats (mudflats into saltmarshes and vice-versa). It is also relevant to consider the longevity of these newly created habitats as most sites are small and confined by realigned coastal protection, and coastal squeeze may resume with continued sea level rise[93].

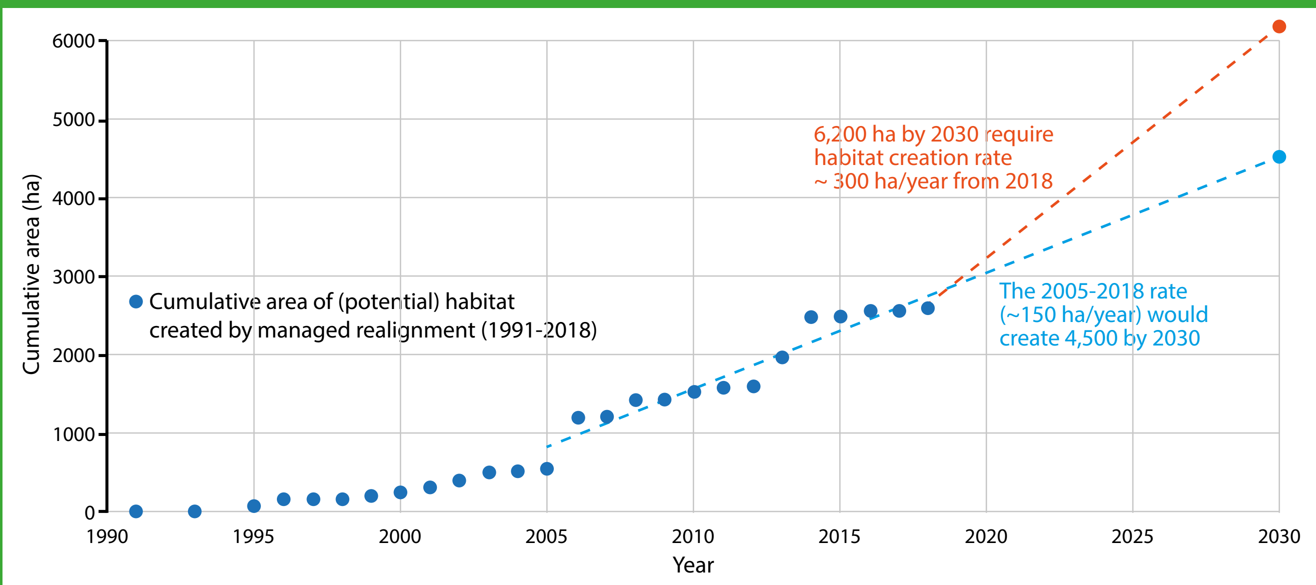

Figure 1. Cumulative area of (potential) habitat created by managed realignment (1991-2018) and projections to 2030 based on current rate (2005-2018) and rate required to create 6,200 ha.

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NATURE-BASED SOLUTIONS AND THE BUILT ENVIRONMENT

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1. KEY POINTS

1. The novelty of nature-based solutions (NbS) for cities lies in a focus on the cost-effective provision of multiple co-benefits for many urban residents.
2. A participatory placemaking approach to equitable co-design, co-creation and co-management of NbS that include multiple stakeholders and beneficiaries has the potential to maintain or improve biodiversity while simultaneously addressing societal issues such as climate change and other socio-environmental inequalities across both spatial and temporal scales.
3. NbS harnesses blue and green infrastructure, such as sustainable drainage systems (SuDS), green roofs, rivers, urban trees and community green spaces, which support significantly higher levels of biodiversity than constructed 'grey' infrastructure. These features can also help urban areas adapt to increased and more extreme temperature and rainfall events associated with climate change whilst delivering important environmental, social and economic benefits.
4. Due to the multidisciplinary nature of NbS, its implementation in cities is inherently complex and at odds with many siloed governance structures, largely due to knowledge and skills gaps and the lack of coordination across sectors or departments, particularly at local authority level.

2. INTRODUCTION

In the United Kingdom, 83% of people live in urban areas[1]. Urbanisation brings a range of intertwined sustainability and resilience challenges. These can include local environmental issues such as poor air quality[2], susceptibility to water pollution and flooding[3], excessive noise[4], and urban heat islands[5]. These impacts ultimately limit the ability of a city to support urban biodiversity and respond to climate change, while also degrading human health and wellbeing, and liveability[6].

Urban areas also provide key opportunities for the implementation of the Sustainable Development Goals[7,8]. Nature-based solutions (NbS) are a tool for enhancing sustainability of urbanisation while simultaneously improving the environment and human wellbeing[9]. As in non-urban areas, the effective implementation of NbS in urban areas has great potential for climate adaptation and mitigation[10], along with a suite of co-benefits such as the enhancement of place attractiveness, of health and quality of life, and creation of green jobs[11]. Socio-economic and socio-cultural challenges frequently drive urban priorities, create partnerships, and unlock financing, and are therefore key to the effective and lasting design, delivery, and maintenance of NbS in the built environment.

Key to the successful implementation of NbS in cities is the recognition that environmental drivers, including biodiversity conservation and climate change mitigation and adaptation, cannot be addressed in isolation. Coordinated efforts and inter-disciplinary partnerships are needed to simultaneously address the complex interactions between environmental, economic and social stressors. The COVID-19 lockdowns in the UK altered how we move around our towns and cities and interact with nature. Restrictions on travel underline the importance of local spaces for connecting with nature and enhancing health and wellbeing. Urban NbS strategies should build off this renewed appreciation for accessible greenspace, and we must also take this opportunity to ensure that the benefits of NbS are distributed fairly and equitably among urban communities.

There are many definitions of NbS, with the IUCN and the European Union providing the most widely accepted expositions. This chapter focuses largely on the ecological aspects of NbS for climate change and biodiversity in the built environment. Wellbeing, health, social inequality and educational attainment, for example, are all relevant issues for NbS to address more widely; however, these have not been analysed in depth here. Therefore, to be effectively implemented and maintained in the long-term, NbS interventions should be embedded holistically within a wider framework that results in multi-functional outcomes. An inclusive, place-based approach accommodates the interplay between these environmental, social and economic elements which together provide NbS.

3. CLIMATE CHANGE MITIGATION POTENTIAL

There are significant opportunities in urban environments for NbS to tackle the causes of climate change and help meet global goals for greenhouse gas emission (GHGs) reductions to mitigate climate change.

3.1 BROWNFIELD SITES

Brownfield sites (defined as land which has previously been developed, the term covers contaminated, vacant or derelict land or land occupied by an unused building, for example[12]) in urban areas have significant potential to act as NbS for carbon sequestration, which can be combined with other interventions to achieve multi-functionality across outcomes including biodiversity and health and wellbeing (see sections 5 and 6). Research in north-east England showed that the retention of fine material derived from demolition on urban brownfield land promotes calcite precipitation in soils and resultant carbon sequestration with no detrimental effect on drainage[13]. Providing a source of calcium in the form of crushed concrete or other sources to just 1% of the UK's urban and suburban soils, could remove up to 1 million tonnes carbon dioxide annually (t.CO_2/yr)[13].

3.2 URBAN TREES

Urban trees also have substantial potential for carbon sequestration, alongside their climate adaptation and biodiversity benefits. For example, the city of Leicester covers approximately 0.03% of Britain's land area but accounts for approximately 0.2% of Britain's aboveground carbon store with around 231,521 tonnes of carbon stored[14]. Approximately 97.3% of this is attributable to trees.

However, aboveground vegetation is not a permanent sink, thus:

1. Tree species need to be chosen and located with care to ensure a long, productive life[15].
2. Management activities (e.g. chainsaws for tree maintenance) should be altered to minimise fossil fuel consumption[14].
3. Tree species should be assessed based on future climate resilience as well[16].
4. Policies should support a net increase in the number of trees over time.

Increasing tree cover on grassland and maintaining this for the long term can increase a city's carbon sink. For example, this study has also shown a 10% increase in tree cover in Leicester, UK, would correspond to a 12% increase in the city's existing vegetation carbon stock[14]. However, possible tradeoffs for this action would include negative social impacts such as increased traffic safety concerns due to obscured lines of sight, loss of biodiversity associated with other habitat types (e.g. species-rich grassland), and the loss of grassland recreation space which would have to be carefully managed. As such, those responsible for tree planting will require the knowledge to adequately assess the appropriate tree for the local conditions, driven by the right reasons and accounting for both temporal and spatial considerations.

4. CLIMATE CHANGE ADAPTATION POTENTIAL

Built environments are facing a unique set of climate change challenges that will test traditional infrastructure and disrupt the daily functioning of cities. Alongside the mitigation potential of NbS in urban areas, NbS are also important in helping urban areas adapt to climate change effects that we know are already starting to take place.

4.1 WATER AND FLOODING

Widespread flooding events have revealed that traditional piped sewer systems and channelised urban waterways cannot be easily adapted to deal with increased rainfall due to the high costs and time associated with maintenance and installation[17]. Sustainable drainage systems (SuDS), which include components such as raingardens, permeable pavements, swales and wetlands, are designed to manage surface water in a way that mimics natural drainage processes as well as providing biodiversity and amenity benefits[18].

A network of inter-connected SuDS integrated into grey infrastructure can reduce costs associated with infrastructure maintenance and water management[19]. Adaptation of existing 'grey' infrastructure will require expensive upgrades to cope with climate change impacts. As such, an expansion and better integration of NbS into cities and new developments will reduce these adaptation costs, mitigate dependency, and reduce redundancy. Green roofs provide stormwater management in highly urbanised environments, which will be important for mitigating the impacts of flooding and adapting these areas to the increased rainfall associated with climate change. Research on green roofs indicates that average water volume retention is 34% and so it can be inferred that each green roof could reduce annual runoff rates in many parts of the UK by 300mm, compared to conventional roof runoff[20]. Near coastal towns and cities, saltmarsh restoration can play an important role in protection from rising sea levels (see the *Chapter 7: Coastal and Marine Systems*).

4.2 TEMPERATURE

Due to the 'urban heat island effect', cities experience average day and night temperatures 1.0 to 3.0 degrees Celsius (°C) warmer than surrounding natural and agricultural areas[21], which can adversely impact both human wellbeing and biodiversity. In addition to overall warming, the frequency of extreme heat events in the UK is projected to increase, becoming the norm between 2030 and 2050[22]. Energy demands for cooling will increase markedly unless better building design and NbS – such as street trees, green roofs and other urban greening - can mitigate these temperature impacts through a cooling effect through shading and evaporation for example.

Urban blue and green infrastructure (BGI) offer significant potential in moderating increased summer temperatures and should be protected and enhanced where possible. For example, the current greenspace in Greater London (approximately 47% of its area) was estimated to cool air temperatures by >0.5°C on clear, still and warm nights[23]. In the Glasgow and Clyde Valley region, a 20% increase in green cover was projected to be able to reduce future average summer temperatures by 0.3°C, which is a third of the additional warming expected by 2050[24]. Green roofs, whilst managing stormwater, also contribute to urban cooling and greater thermal efficiency of buildings[25,26]. Even small urban green spaces, for example community gardens, can help to tackle the heat island effect and have a cooling influence[27]. For full benefits to be realised, it is important that NbS consider a rich variety of horizontal and vertical BGI. There are still knowledge gaps regarding species selection and the optimum design of greenspaces for cooling and further research is needed[28].

4.3 AIR QUALITY

Cities are focal points for the production of air pollutants and particulate matter, of which nitrogen dioxide and carbon dioxide comprise the main air pollutants. As a result, air quality tends to be lower in cities than elsewhere in the UK[29]. Other climate-sensitive air pollutants include ground level ozone and aeroallergens such as pollen. Increases in temperature as the climate changes will, for example, lead to changes in the chemistry and chemical reactions associated with these pollutants, e.g., ozone formation, as well as dispersal and deposition that could lead to secondary pollutants with additional consequences[30]. Even short-term exposure to ground-level ozone and particulate matter increases mortality as well as respiratory diseases, lung cancer and cardiovascular hospital admissions.

Air pollution has been deemed the largest environmental risk to public health in the UK with 40,000 premature deaths each year attributable to exposure to outdoor air pollution[31], affecting people with underlying health conditions and those from deprived communities the most. The health effects associated with air pollution also directly impact worker productivity, resulting in over six million sick days a year in the UK[31]. We know that weather and climate influences pollen production, but it remains unknown how allergies will be affected by higher temperatures, high concentrations of carbon dioxide, and different patterns of rainfall and humidity that may be associated with extended growing seasons[22].

Vegetation and trees can absorb or intercept airborne particulate matter (PM) and other aerial emissions, as well as sequestering carbon dioxide. PM is intercepted by trees through a number of processes, including 'dry deposition' in which the particulate matter is deposited on the surface of leaves and some of this is permanently incorporated into leaf wax or cuticle[32]. Modelling shows that current tree cover in Glasgow removes three per cent of the primary PM_{10} [33]. The extent to which trees remove PM is inconsistent and influenced by a number of factors, including tree species identity. Tree species should be carefully selected to avoid species that are known to be high emitters of biogenic volatile organic compounds as these compounds can lead to negative impacts on air quality[33]. Additionally, the choice of plant species which are known sources of aeroallergens should be avoided[33].

Trees can also play a role in removing ultrafine particles (UFP) which are believed to contribute to the toxicity of PM, although the magnitude of this is currently uncertain[34]. The choice of tree species is also important in this context and evidence has shown that silver birch was the most effective species at removing UFP, closely followed by yew and elder[35]. Young silver birch trees along roads were also associated with major reductions (60–80%) in adjacent indoor concentrations of PM[34].

5. BIODIVERSITY VALUE

Achieving biodiversity goals in urban areas will require a greater focus on the species and genetic elements of biodiversity conservation and restoration, including monitoring for early detection of invasive species. It will also require the engagement of local people and communities on biodiversity objectives. Protecting remnant urban green spaces will also be important for biodiversity, in addition to reducing habitat fragmentation through appropriate placemaking and planning decisions, and conservation of existing green space to maximise connectivity.

For some taxa, especially birds, beetles, butterflies and mammals, diversity is greatly reduced by intense urbanisation, while moderately built environments can support higher diversity of some groups[36,37,38,39]. For example, bee species richness in UK cities appears higher than in surrounding farmlands and equivalent to nature reserves[40]. Built environments typically harbour high plant diversity through the landscapes and novel habitats created by humans[41], though abundances of native species are often quite reduced[42,43], and cities frequently struggle with invasive species impacts[44]. Large green spaces provide indispensable habitat for species, buffering diversity against the direct and indirect urban drivers of biodiversity change[45,46,47].

Artificial habitats incorporating natural features, such as SuDS and green roofs support significantly higher levels of biodiversity than constructed 'grey' infrastructure (e.g. roadside culverts, asphalt roofs), but not as high levels as remnant natural areas in cities (e.g. ponds, urban meadows) which should be retained[48]. For example, research highlights the potential biodiversity benefits that green roofs can provide, including habitat provision for black redstarts, as seen in London[20]. NbS should be integrated throughout existing urban green spaces thereby improving connectivity for wildlife movement (e.g. insects[49]).

Brownfield sites could also offer an opportunity to support biodiversity conservation by providing analogous conditions to natural habitats and for example helping maintain populations of some rare and scarce species[50]. As a result of the importance to biodiversity, 'open mosaic habitats on previously developed land' is recognised as a UK BAP (Biodiversity Action Plan) priority habitat. This priority habitat typically consists of some bare ground, vegetation which can be in the process of transitioning from one vegetation type to another[51] and more established grassland. Brownfields can mimic many of the traditional habitats used by rare butterflies which have declined in the countryside. Additionally, many brownfield sites can support plentiful amounts of larval foodplants. In terms of managing sites specifically for biodiversity, rotational disturbance in scattered areas around a brownfield site is one example of a method that can help encourage a successional mosaic with diverse vegetation, which can benefit scarce bumblebees and butterflies[52].

Retaining suitable brownfield sites or areas thereof as managed areas of conservation has the potential to have multiple beneficial impacts on urban biodiversity and human wellbeing, provided it is feasible, appropriate, and integrated within a holistic, community-oriented NbS approach and does not exacerbate or ignore existing socio-environmental inequalities.

6. HUMAN WELLBEING VALUE

Urbanisation is one of the most significant health issues of the twenty-first century (see section 4). The increasingly built environment affects our ability to access and connect to nature. Interactions with nature are largely driven by opportunity (for example access to quality and quantity greenspace) as well as peoples' orientation to nature (for example through participation in activities in nature, or regular outdoor play as children)[53,54].

Some NbS in urban environments have the potential to provide multiple health and wellbeing benefits. Street trees provide habitat for animals that capture people's fascination, like songbirds, mammals and butterflies, and make for more pleasant neighbourhoods that encourage people to walk or cycle and engage more directly and frequently with their local green space. It has been shown that the presence of a healthy urban forest reduces cardiovascular and pulmonary illness[55].

Research demonstrates the remarkable range of beneficial health outcomes from exposure to nature[56], but there is a trend of declining nature experiences in urban populations[57,53]. Moreover, the most deprived communities often have less access to green space[58] and exposure to biodiversity[59,60]. Not only is this a significant environmental justice and equity problem (discussed further in the *Chapter 9: Embedding NbS in Strategic Spatial Planning*) but given the positive association between exposure to nature and pro-environmental behaviour demonstrated through studies in England, these patterns could be hindering the realisation of sustainability targets[61]. The values that people hold, which therefore influence behaviours such as consumption and issues of governance and accountability, have been recognised as one of the indirect drivers of biodiversity loss, and is thus central to solving the direct drivers of biodiversity loss[62].

Urban areas often include brownfield sites, particularly in areas of higher deprivation[63]. Communities near brownfield sites tend to have poorer health and life expectancy, increased crime and antisocial behaviours, environmental and health impacts of contaminated land, economic costs of remediation, and multiplier effects of visible and clustered brownfield sites, with the health and wellbeing impacts disproportionate in areas of multiple deprivation[64]. Through working with local communities, these sites have the potential to become resilient, accessible, and useable assets with considerable health, economic, climate and biodiversity benefits across local and regional spatial scales. One of the Sustainable Development Goals is to reduce inequality, so the hidden drivers that lead to "green gentrification" – the exclusion and displacement of disenfranchised communities or increasing land values – must be accounted for in order to avoid further compounding existing socio-environmental inequalities[65].

7. NBS TO IMPROVE THE ECONOMY

NbS can provide substantial economic benefits including increased population health and wellbeing, reduced costs associated with climate change impacts, the creation of green jobs, reduced social, environmental and economic costs of brownfield sites, and increased lifespan of essential urban infrastructure[66]. Further, accessible and multifunctional NbS can serve as a form of local investment that can spur economic growth and community revitalisation.

Climate change poses the greatest long-term risk to traditional grey infrastructure performance. Flooding already accounts for significant losses in infrastructure services, with outages tending to last longer than other weather-related hazards (usually several days or even weeks). The growing risks from heat, water scarcity and slope instability caused by severe weather can lead to a reduction in a standard of protection: concrete infrastructure deteriorates faster if subjected to more frequent and extreme periods of freeze–thaw, while prolonged hot dry periods are likely to accelerate desiccation of surface soils on earth embankments, affecting stability[22].

NbS can reduce the significant costs associated with adapting grey infrastructure to climate change, as well as the comparative management and maintenance costs, whilst simultaneously providing multiple social and environmental co-benefits that grey infrastructure is not designed to provide. In general, neither the short- nor long-term economic benefits of NbS have been fully quantified. The value of urban trees provides perhaps the most comprehensive assessment of benefits. What is clear from these assessments is that urban trees provide immense value in direct and cost-saving benefits[67]. Attempts to account for the monetary value of ecosystem benefits have shown that natural systems add millions of pounds of value to cities[68]. For example, Birmingham, in one of the first attempts to produce a comprehensive valuation of urban habitats, valued its ecosystem services at £11.66 million per year, but also recognised that this was a substantial undervaluation[69].

For the City of London, the annual economic contribution of its eight million trees was estimated to be £132.7 million annually, or about £15 per tree[70]. Economic benefits include the evaporative cooling provided by the trees and how this increases air-conditioning unit efficiency, as modelled in three UK urban areas (Edinburgh, Wrexham and London). This cooling from urban trees was predicted to save up to £22 million in annual energy consumption across inner London alone[71]. Many other intangible benefits that are difficult to monetise result from interaction with urban trees and these are increasingly valued among people and society[72,73].

8. CHALLENGES

The implementation of NbS in cities is inherently complex because of multiple, sometimes competing views on the design of urban space[74]. This complexity is compounded by the fact that NbS require the consideration of multiple benefits across environmental, ecological, societal, economic and community dimensions. The multidisciplinary nature of NbS is at odds with most governance structures and the lack of coordination across sectors or departments, particularly at local authority level, and so this is a challenge that actively needs to be addressed[75].

Interdisciplinary partnership working is needed to deliver NbS that meet multiple outcomes in urban areas. A lack of capacity in many organisations and local authorities, and skills gaps, particularly around designing and adapting NbS to local conditions, need to be addressed. Further, the declining budgets available to local authorities to invest in and manage urban green infrastructure (including large municipal parks and Country Parks)[76] also needs addressing. Given the particular socio-economic and socio-cultural challenges facing some urban communities, it is particularly important to integrate a participatory placemaking approach to equitable co-design, co-creation and co-management of NbS that include multiple stakeholders and beneficiaries, with the social impacts of NbS explicitly considered.

Integrating multiple forms of NbS and allowing for mixed-use planning on larger sites, whilst moving away from singular outcomes towards multiple outcomes is, therefore, particularly important. Better and long-term monitoring and evaluation are needed to produce stronger evidence that captures the broad values and benefits associated with NbS, including how impacts differ across different social groups.

CASE STUDY 1: A DIVERSE RESEARCH AND INNOVATION AGENDA FOR NATURE-BASED SOLUTIONS AND RE-NATURING CITIES

Given the complex nature of urban NbS and that design, implementation and management can include different actors and objectives, there have been a high diversity of project started across the world. Projects span the full gamut, from local grassroot community initiatives to re-nature a neighbourhood to international NGOs that provide guidance and recognise city NbS initiative. Here we highlight five example projects to highlight the multi-actor and multiple dimensions of NbS implementation.

[1]https://ec.europa.eu/research/environment/index.cfm?pg=nbs

[2]https://ec.europa.eu/easme/en/news/nature-based-solutions-are-helping-address-urban-challenges

Example projects [2]

- **NATURVATION** aims at developing the understanding of what NbS can achieve in cities, examine how innovation can be fostered in this domain, and contribute to realising the potential of NbS for responding to urban sustainability challenges by working with communities and stakeholders. Six cities are partners in NATURVATION – Barcelona, Győr, Leipzig, Malmö, Newcastle and Utrecht (https://naturvation.eu)
- **Connecting Nature** forms a community of cities fostering peer-to-peer learning and capacity building among front runner cities that are experienced in delivering large scale NbS and fast follower cities that have the desire to implement large scale NbS but lack the expertise. The 11 cities participating in this project are: Glasgow, Genk, Poznan, La Coruna, Bologna, Burgas city, Ioannina, Malaga, Nicosia, Sarajevo and Pavlos Melas (https://connectingnature.eu/)
- **GrowGreen** aims to create climate and water resilient, healthy and liveable cities by investing in NbS. Demonstration projects are designed and implemented in four Frontrunner Cities – Manchester, Valencia, Wroclaw and Wuhan. These cities are paired

with Follower Cities: Brest, Zadar and Modena (http://growgreenproject.eu).

- **UNALAB** aims at addressing the challenges that cities around the world are facing today, by focusing on climate and water related issues through innovative NbS. With three demonstration cities (Tampere, Eindhoven and Genova) and seven replication cities (Cannes, Prague, Başakşehir, Castellón, Stavanger, as well as Buenos Aires and Hong Kong) (https://unalab.eu/).
- **URBAN GreenUP** aims at developing, applying and validating a methodology for Renaturing Urban Plans to mitigate the effects of climate change, improve air quality and water management through innovative NbS. The URBAN GreenUP consortium is comprised of eight partner cities - the front-runners (Izmir, Liverpool, Valladolid) and the followers (Chengdu, Ludwigsburg, Mantova, Medellin, QuyNhon) (https://www.urbangreenup.eu/)

CASE STUDY 2: GREEN INFRASTRUCTURE STRATEGIC INTERVENTION, SCOTLAND

Objectives

The Green Infrastructure Strategic Intervention (GISI) is a £15 million European Regional Development Fund programme in Scotland, led by NatureScot. The largest urban NbS intervention in Scotland, it targets areas with a deficit of good quality greenspace, multiple deprivation and an excess of vacant and derelict land.

It enables active and local solutions to clearly evidenced social, economic and environmental needs using green infrastructure (GI) and NbS to create multi-functional places, address inequalities, provide opportunities for better health, support a resilient economy, adapt to climate change, and create space for nature.

The GISI is using its projects as demonstration sites to showcase NbS in practice, exchange knowledge in Scotland and beyond, contribute to wider mainstreaming of green infrastructure and NbS, and influence policy, planning and funding decisions.

Projects

The GISI is funding 14 capital projects with up to 40% gap funding, or around £1 million per project, resulting in an overall programme investment of around £40 million. Projects are being delivered by a range and combination of grantees, including local authorities (LAs), housing associations, Scottish Canals, and the NHS. Each project is profiled on the GISI website. For a detailed example on Financing NbS, please see the Financing NbS Case Study in *Chapter 11: Economic Valuation and Investment Options for Implementing Nature-based Solutions*.

Many projects include vacant and derelict land (V&DL) sites and as a result of stipulated outcomes, most include outdoor learning provision, community food growing, habitat creation or enhancement, flood management and sustainable drainage systems (SuDS), improved access and path or active travel networks, and active community involvement through, for example, “Friends of” groups.

Design

Crucially, each project entails co-design, co-creation and co-management with the local community. This ‘co-co-co’ approach helps local communities become more resilient to challenges such as the impacts of climate change. Using GI supports urban biodiversity and provides direct adaptation benefits, such as natural flood management and local cooling, whilst delivering important co-benefits.

Drivers

The GISI projects were conceptualised due to economic and social deprivation challenges, which are multiplied by impacts of climate change. Biodiversity in its own right did not provide a single driver for any project, however, it is one of the GISI’s five required outcomes. Project drivers include, for example: health outcomes; harnessing GI to unlock derelict or contaminated site development; and surface and flood water management.

The projects will be complete by 2023, so monitoring and evaluation is ongoing, and the full extent of the projects’ impacts will become apparent in time.

Source: https://www.greeninfrastructurescotland.scot/

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SECTION 2: EFFECTIVE IMPLEMENTATION AND DELIVERY OF NATURE-BASED SOLUTIONS

EMBEDDING NATURE-BASED SOLUTIONS IN STRATEGIC SPATIAL PLANNING

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1. WHY IS SPATIAL PLANNING IMPORTANT FOR DELIVERING SUCCESSFUL NATURE-BASED SOLUTIONS?

Land in the United Kingdom (UK) is under intense pressure to meet growing demands for housing, infrastructure, food, timber, biofuel, fresh water, recreation, and carbon storage and sequestration, while also trying to make space for nature and reverse the decline in biodiversity. Nature-based solutions (NbS) can help to meet these multiple needs at low cost, but only if they are integrated into a strategic spatial planning approach which can balance these competing demands at landscape scale.

Effective spatial planning can optimise land use, exploiting synergies where possible and managing the inevitable trade-offs. This will deliver the right NbS in the right places, and ensure that the land-use system as a whole can meet local, regional, national and international needs. Bad planning, or lack of planning, can result in poor outcomes or even in decisions that do more harm than good. Some examples of good and bad planning of NbS are given in Box 1.

BOX 1: EXAMPLES OF GOOD AND BAD SPATIAL PLANNING FOR NATURE-BASED SOLUTIONS

Good planning

- ✓ Use of spatial planning to locate
  - new green space close to deprived communities, to maximise health and wellbeing benefits.
  - woodland strips and hedges between transport infrastructure and houses or schools to act as air pollution and noise barriers.
  - Place new trees in areas which contain a lot of hard surfaces such as city and town centres to mitigate the effects of high summer temperatures
- ✓ Using a landscape/catchment planning approaches to place woodlands for flood and erosion protection on steep, erodible slopes upstream of flood zones, informed by hydrological modelling to avoid synchronisation of flood peaks.
- ✓ Embedding NbS within Nature Recovery Networks and Strategies and choosing a diverse mix of native species and habitats that will support local wildlife and be resilient to future change.

Bad planning

- × Poorly planned afforestation driven largely by numerical targets, that results in planting trees on scarce semi-natural grassland or heathland habitats, thus destroying rare species, or on peaty soils which will dry out resulting in more carbon emissions.
- × Conversion of high-quality farmland to other uses such as woodland or green space, resulting in displaced impacts as more land is used to produce food elsewhere.
- × Afforestation which does not consider the right species/variety mix in the right place or focuses solely on planting monocultures of non-native tree species. This may fail to deliver biodiversity and other benefits and stands could be vulnerable to climate change, pests and diseases.

The planning systems in the UK suffer from fragmentation, with multiple policies and actors governing different sectors within the same geographic space. While approaches differ between the countries and some recent attempts have been made to partly address this[2], this is largely the case across the UK. For example, in England the National Planning Policy Framework (NPPF) for town and country planning; the forthcoming Environmental Land Management scheme (ELMS) for agriculture; regulators such as Water Services Regulation Authority, Office of Gas and Electricity Markets, Office of Communication and Office of Rail or Road for water, energy, communication and transport infrastructure; Natural England, the Forestry Commission and the Environment Agency for biodiversity, forests, air and water quality; and the Building Regulations Advisory Committee and the National Infrastructure Commission overseeing built infrastructure. Each system has its own governance, limiting the development of holistic solutions which can deliver better environmental, social and economic outcomes. The relevant legislation, agencies, goals and objectives across these sectors at national and local level need to be better synchronised[1,2]. In this chapter we show that mainstreaming NbS into spatial planning policy can help to address this disintegration, by developing landscape-wide plans that transcend different sectors and bring all relevant stakeholders together to jointly agree on a spatial vision.

2. HOW TO PLAN SPATIALLY COHERENT NATURE-BASED SOLUTIONS

A variety of landscape-level planning approaches relevant to NbS exist or are emerging, including the Ecosystem Approach[3], Local Plans, Local Natural Capital Plans, Catchment Management Plans, Landscape Enterprise Networks, Nature Recovery Networks and Nature Recovery Strategies, Local Nature Partnerships (LNPs), Regional Land Use Partnerships and Farmer Clusters. These approaches are generally participatory, interdisciplinary and evidence-based. They aim to balance conservation of biodiversity and the sustainable use of natural resources with fair and equitable sharing of the benefits, using negotiation to resolve any trade-offs, and using an adaptive management approach to monitor and learn from the outcomes. Early engagement across sectors and disciplines is vital, bringing stakeholders together to jointly determine priorities for strategic land-use investments rather than developing sector specific plans and strategies, and transcending traditional environment, health, economy and housing silos. Figure 1 suggests how such an approach could be applied to planning NbS – starting with jointly defining a vision for the area, then developing an evidence base, prioritising opportunities for NbS to meet stakeholder needs, and finally delivering, managing and monitoring NbS as part of a process of adaptive management which can respond to future change. In the following sections we discuss each of these stages in turn, illustrating them with case studies.

2.1. BRINGING STAKEHOLDERS TOGETHER AND DEVELOPING A VISION

NbS planning should be grounded in the local context and should reflect stakeholder priorities, to gain local support and avoid conflict[4]. It is important to identify and bring together all stakeholders - policy-makers, landowners, practitioners implementing the schemes, and beneficiaries - to identify their goals, values and priorities and develop a joint vision for the area. Engaging stakeholders and communities in this process also facilitates understanding of the institutional and emotional perspectives of spatial planning[5]. For example, the Green Infrastructure and the Health and Wellbeing Influences on an Ageing Population (GHIA) value tool uses an online

[2] The Wellbeing of Future Generation Act in Wales requires public bodies to consider a single set of goals and act in a long-term and integrated way.

VISION

- Identify all relevant stakeholders and bring together in a participatory forum
- Consult with local communities to identify local views and values
- Identify local, regional, national and international challenges, goals, priorities and drivers of change

EVIDENCE

- Map existing natural capital assets and their ability to deliver ecosystem services
- Identify local Nature Recovery Networks and Nature Recovery Strategies
- Who and where are the beneficiaries?

OPPORTUNITIES

- Identify gaps between supply and demand. How can NbS maximize socio-economic benefits?
- How can NbS be integrated into Nature Recovery Networks and Strategies?
- How can local, regional and international priorities, challenges/drivers of change be considered in NbS decison making?
- Plan at landscape scale to maximize synergies, minimize trade-offs and ensure all needs are met

DELIVERY

- Identify and prioritise a pipeline of investment-ready projects
- Identify and create frameworks to develop sustainable flows of investment funds
- Implementation, monitoring and adaptive management of NbS

Figure 1. Strategic spatial planning for NbS, following a participatory ecosystem management approach.

survey to map the values that residents in Greater Manchester place on their green and blue spaces[6], and similar surveys have been carried out in Bicester[7] and Sheffield[8].

As well as consulting with local communities to identify local views and values and understand local priorities, it is important to consider regional priorities (e.g. for flood protection or water supply at the catchment scale), national priorities (e.g. for food security), and global goals (e.g. for climate change mitigation). Synergies between goals can be identified, for example by integrating NbS with Nature Recovery Networks, and supporting locally important species and habitats. The vision-setting process may identify potential conflicts and trade-offs between goals; these can often be minimised by careful planning. For example, conflicts with food production could be reduced by avoiding the conversion of high-grade agricultural land to other uses, while also implementing NbS such as buffer strips, species-rich field margins and creating hedgerows to reduce adverse impacts on the surrounding environment.

There are many collaborative groups across the country that bring together stakeholders to support and implement NbS. For example the Liverpool City Region's LNP, 'Nature Connected', has a dedicated Natural Capital Working Group with partners from the third sector, local government, business and academia, that has had success in policy advocacy, resourcing and evidence generation for spatial planning of NbS[9,10]. Case Study 1 illustrates how different organisations have worked together to implement an integrated approach in Greater Manchester.

CASE STUDY 1. STAKEHOLDER PLANNING FOR NATURE-BASED SOLUTIONS IN GREATER MANCHESTER COMBINED AUTHORITY (GMCA)

The Greater Manchester Natural Capital Group (NCG) was established in 2013 as a result of UK government's 2011 'Natural Environment White Paper', acting as the LNP for the city region. The strategic planning process has been built on a natural capital narrative. The work is underpinned by a robust evidence base building on a natural capital assessment undertaken across the whole area[11], including opportunity maps for ecosystem services[12]. This was enabled via the Department for Environment Food & Rural Affairs (DEFRA) pioneer programme and European Union funding, which allowed them to test out new approaches to the delivery and mainstreaming of natural capital.

NCG has an action plan with clear targets and accountabilities, and reports to the Green City Partnership Board on delivery of those actions. Actions show who delivers across stakeholder partners and the progress they are making. The Green City Region Partnership Board, in turn, reports to GMCA. Each leader of the ten local authorities has a portfolio on these different groups, forging a strong partnership approach with political leadership. Securing the early and active support and championing of Andy Burnham as Mayor was also critical, with a Five Year Environment Plan launched in 2019[13] and a commitment to be carbon neutral by 2038. A "Call to Action" enabled a partnership approach to flourish, with task groups established for each priority area in the Five Year Environment Plan. The results from this include:

- Strategic policy – natural environment firmly embedded within actions set out in the Five Year Environment Plan
- Biodiversity net gain – commitment in emerging Greater Manchester Spatial Framework for 10% net gain, with Salford Council the first to include as part of their local plan consultation
- Securing €5m for the IGNITION project to support the delivery of NbS business models
- Production of a natural capital investment plan and development of a Greater Manchester environment fund
- Communication and engagement – value of natural environment firmly embedded as part of Greater Manchester natural environment vision, and engagement toolkit recently launched

2.2. BUILDING THE EVIDENCE BASE

NbS plans need to be informed by good evidence. This includes the location and quality of existing natural capital assets and the ability of these assets to deliver ecosystem services. The location of potential beneficiaries for each ecosystem service, the demand for these services, and any gaps between supply and demand allow identification of opportunities for NbS to meet the needs of beneficiaries. Understanding how the natural assets form ecological networks and the movements of species across them is also key.

Spatial analysis helps to understand where existing high value natural assets need to be protected, and where to avoid NbS interventions that might lead to perverse outcomes, for instance, through the substitution of a higher value habitat. Effective mapping also helps to provide a robust baseline for monitoring change.

There are a number of spatial natural capital datasets available at national level in England (see Wigley et al 2020[14] and Dales et al 2014[15]), Wales (see Emmett et al 2017[16]) and Scotland (see McKenna 2019[17]). While these national assessments utilise different approaches they are not designed for or are too coarse for local planning. Some regions in the UK have been developing finer scale spatial maps of natural capital assets, ecosystem service flow and in some cases ecosystem service demand often aimed at informing local spatial planning (e.g. Holt et al 2019[18], Smith 2019[19], see Case Study 2). These methods draw on nationally available data (including Ordnance Survey data and Natural England priority habitat data), in some cases supplemented with local habitat data provided by Local Environmental Record Centres or other local sources.

Local habitat data or ground-truthing surveys can considerably improve the accuracy of the maps. For example, ground-truthing of a map of the Dane Catchment, Cheshire, using only nationally available data, found that 78% of habitat land parcels were identified correctly[20], while a comparison for the Oxford-Cambridge Arc found that local habitat data identified an additional 20,000 hectares (ha) of semi-natural grassland that was missing from maps generated using only national datasets[21]. However, collecting this data can be time consuming and requires a level of resource not often available to local or regional government. Local Environmental Record Centres across the UK play a key role in coordinating and training citizen science volunteers, and verifying the collection of such data, but need increased funding to expand this in a systematic and comprehensive way. Software applications can also help with the verification process. This could build on the success of tools such as the I-naturalist which have been shown to be viable in assisting citizen science species identification and recording alongside expert verification[22]. Citizen science activities and apps have the potential to help gather data on habitats condition and the influence of land management, which is usually neglected due to lack of data. For example, the LandApp tool is being developed for farmers to map the habitats and management approaches on their farms, in order to inform design of farm management plans to develop NbS interventions that provide public goods[23].

CASE STUDY 2. NATURAL CAPITAL MAPPING AND TREESCAPES IN OXFORDSHIRE

In Oxfordshire, there is an urgent need to map existing natural capital assets in order to help guide plans for large scale housing and infrastructure development, with plans to double the number of houses in just 30 years. A relatively quick and simple method of mapping natural capital was developed and tested with stakeholders, based on a matrix of scores for the ability of different habitats to deliver each of 18 different ecosystem services[19]. The maps reveal networks of strategic high value natural capital assets that need to be protected from inappropriate development, especially along river valleys, and these overlap to a large extent with the Nature Recovery Networks for Oxfordshire.

This method has now been extended to inform the development of local natural capital plans across the Oxford-Cambridge Arc[21] (see https://www.oxcamlncp.org/). It is also informing the development of a new Tree Opportunity Map (see https://www.oxtrees.uk/mapping) which aims to develop county-wide guidelines based on delivering the 'right trees in the right place', ensuring a balanced mix of 'Treescapes' for timber, carbon, flood protection, recreation and nature across the county.

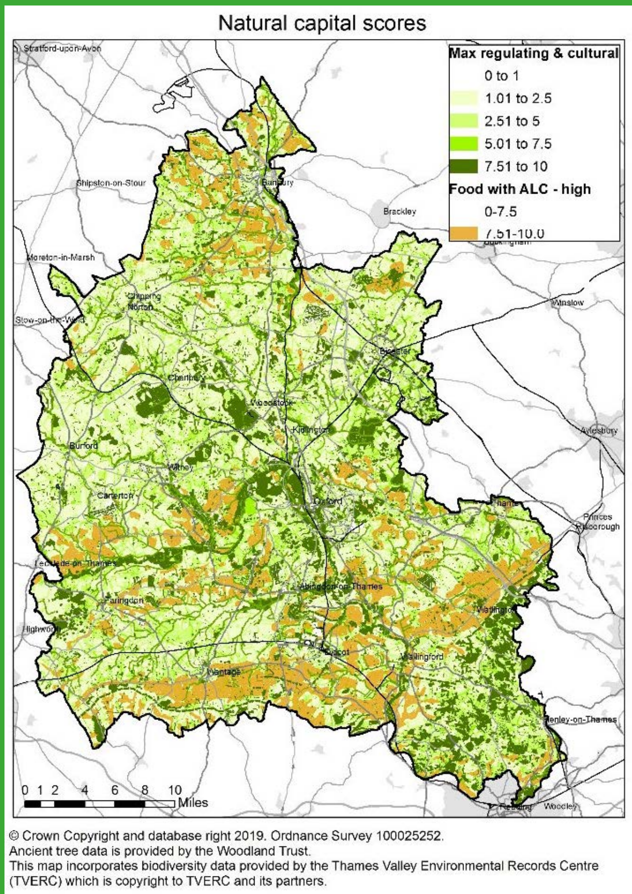


Figure 2. Natural capital assets in Oxfordshire[19]. Darker shades of green indicate higher value for regulating and cultural services (maximum score for any regulating or cultural service), while orange indicates high value areas for food production. Reproduced with permissions from Alison Smith.

2.3. IDENTIFYING AND PRIORITISING OPPORTUNITIES FOR NATURE-BASED SOLUTIONS

Having defined a vision and mapped existing assets, the next step is to identify opportunities for NbS to meet stakeholder needs. This can be done by assessing the demand for the benefits and services that NbS can deliver (or in other words, the problems that NbS need to address), and then comparing this with the maps of ecosystem service supply to identify any gaps which signal an unmet need.

Demand maps can be developed by combining different factors such as data on deprivation level, health needs, population size, areas at risk of flooding, sources of pollution, or access to greenspace. There is considerable evidence to indicate that health and wellbeing inequalities are exacerbated by poor access to high quality environments including those that provide NbS[24]. Identifying "pinch point" areas where demand for NbS is high but provision is low can help to highlight areas of environmental inequality (see Case Study 3). For example, NbS such as new urban parks or community orchards could be located close to disadvantaged communities in order to maximize health and socio-economic benefits and create green jobs.

CASE STUDY 3. ADDRESSING SOCIAL JUSTICE AGENDAS FOR INVESTMENT IN NATURE-BASED SOLUTIONS: BIRMINGHAM

There has been a lack of attention to the impact of NbS on social justice. Many new schemes involving NbS help to embed nature in new housing developments but while neglecting existing vulnerable and deprived communities who lack access to nature[25]. This case study shows how Birmingham City Council built an innovative evidence base using demand and supply maps of core ecosystem services which, when combined with the index of multiple deprivation, provides a powerful spatial priority map for new investment in NbS. Six ecosystem services were mapped: aesthetics and mobility, flood risk, local climate, education, recreation and biodiversity. These were translated into supply and demand maps showing areas of need and overprovision. These six maps were then super-imposed into a single multi-layered challenge map for Birmingham (Figure 3). The dark areas of red signify the priority areas where there is a combined ecosystem service deficit. Significantly, these areas also map onto places with a high index of multiple deprivation that also suffer a ten-year reduced life expectancy. Tools such as the community infrastructure levy and biodiversity net gain may provide some scope for retrofitting NbS into these deprived spaces.

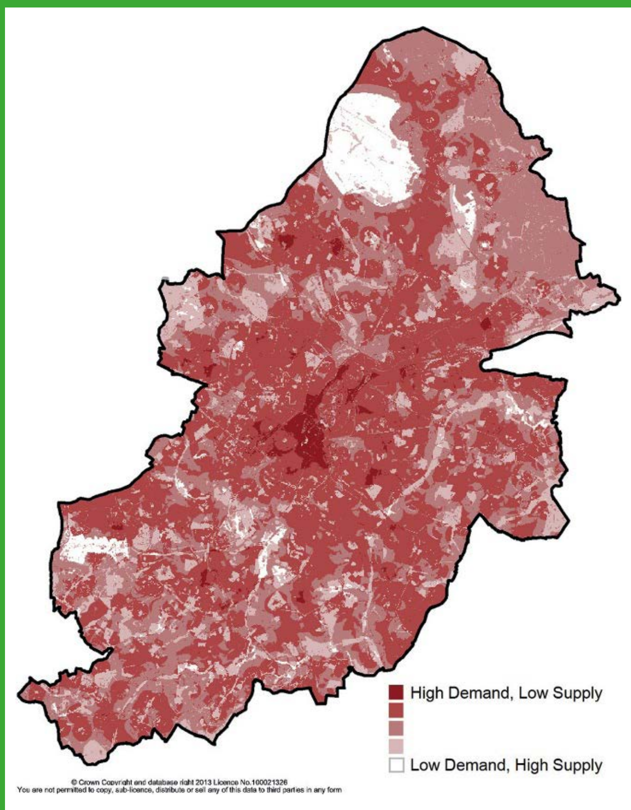


Figure 3. Ecosystem Service Challenge Map for Birmingham; reproduced from Scott *et al.* (2018)[26] (under CC BY 4.0 license).

Benefits for nature can be maximized by integrating NbS into Nature Recovery Networks and Strategies, drawing on ecological network analysis to optimize the connectivity of networks of different habitat types. For example, Rouquette (2018) considered both need for ecosystem services and ecological connectivity to identify potential new sites for NbS for woodland, wet grassland and semi natural grassland in Northampton and Peterborough[27]. In Glasgow and Clyde, ecological networks were integrated with green active transport routes to deliver health and well-being benefits for people, alongside benefits to nature from new habitat creation (see Case Study 4).

CASE STUDY 4. IMPROVING CONNECTIVITY AND NETWORKS IN NATURE-BASED SOLUTIONS: GLASGOW AND CLYDE VALLEY GREEN NETWORK

The Glasgow and Clyde Valley Green Network helped to deliver improved strategic planning through NbS thinking[28] (Figure 4). By focussing on improving connectivity, they have enhanced their strategic Green Network for the benefit of the people, economy and wildlife in Glasgow City Region. There are two components: an Access Network; facilitating the off-road movement of people between communities through greenspace, and a Habitat Network; facilitating the movement of wildlife through the landscape. The Strategic Access Network is comprised of more than 200 routes over 500 miles, but only 60% of the routes are within the Green Network. The resultant Blueprint identifies opportunities to address the on-road sections of the network[28].

The habitat network comprised nearly 40% of wildlife habitat, but these habitats are not well connected. The Blueprint identifies nearly 800 targeted opportunities to better connect Habitat Networks

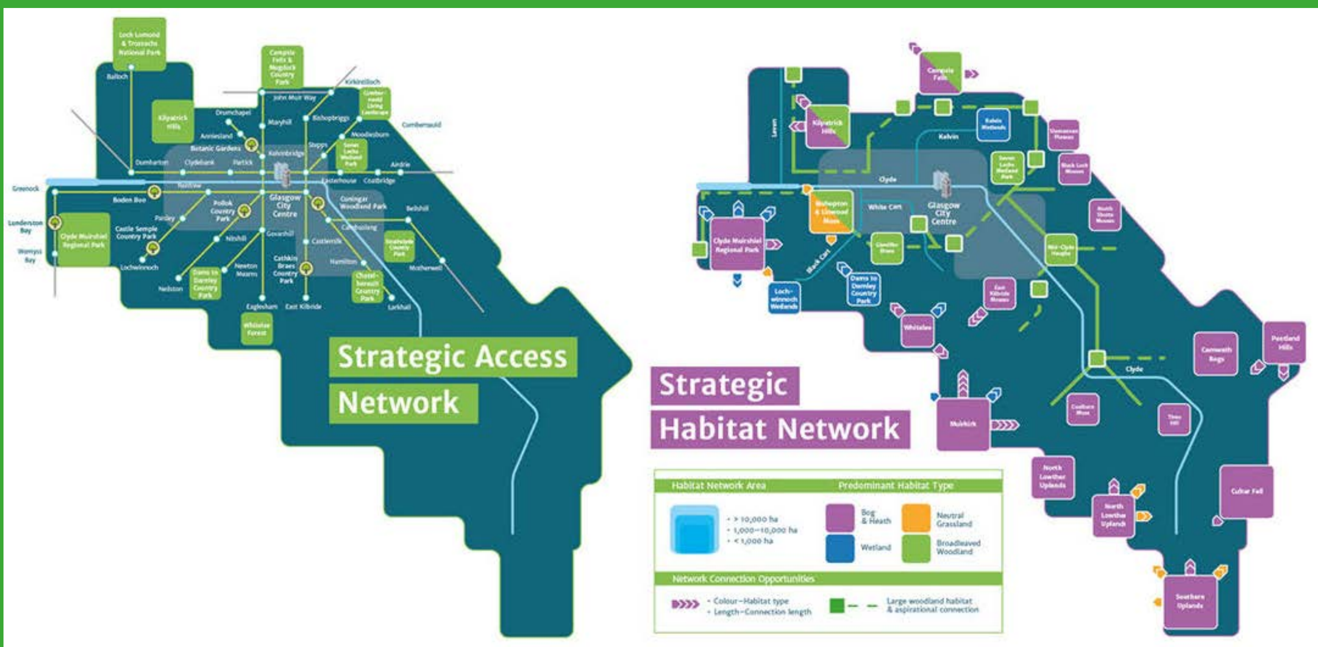


Figure 4: The Blueprint: Glasgow Clyde Valley Green Network[28,29]. Reproduced with permission from GCV Green Network Partnership.

Planning NbS may involve decisions about what type of habitat to restore or create in a given location. In cases where more than one habitat type could be created in a certain location, some form of prioritisation is necessary. This could consider the rarity of habitats at landscape scale: for example, if there is 10% woodland but only 1% heathland and 2% lowland meadow in a region, then heathland or meadow creation could be prioritised rather than woodland on sites that are suitable for all three habitat types. The Nature Networks Evidence Handbook[30] provides 'rules of thumb' to aid practitioners, including a suggested hierarchy of actions to improve core wildlife sites; increase the size of core sites; increase the number of core sites; improve the 'permeability' of the surrounding landscape for the movement of wildlife; and create corridors of connecting habitat, as well as developing several Large Nature Areas (5-12,000 ha) across the country. Other actions to maximise biodiversity benefits include using a diverse mix of native species wherever possible, and including natural regeneration as well as active interventions such as planting trees.

Considering wider socio-economic factors may also play a part in identifying areas for NbS. Spatial data which provide locations such as areas designated for major development, brownfield sites or former mining sites may assist in narrowing down sites for NbS. Consideration of major policy changes or challenges may also have an influence. The Environment and Rural Affairs Monitoring & Modelling Programme (ERAMMP) explored the effects of three different Brexit scenarios on changes in land use in Wales[16]. Based on these scenarios, they identified land where the use may change from agricultural production to NbS such as restored peatland or tree planting due to economic drivers (see Case Study 5).

When evaluating different options, it is important to consider the full range of potential benefits that NbS can deliver, and to actively identify conflicts or trade-offs and decide how to manage them. When individual opportunities for NbS have been identified, the overall impacts should be assessed at landscape scale to ensure that a balanced mix of NbS is delivered to meet all needs.

CASE STUDY 5. CONSIDERING MAJOR CHANGES AND CHALLENGES IN NATURE-BASED SOLUTION DECISION MAKING

Recent work for Welsh Government under the ERAMMP modelled the impacts of plausible agricultural changes due to Brexit on the environment (e.g. water and air quality, greenhouse gas emissions, woodland carbon sequestration) nationally at high spatial resolution[16]. This work also explored regional variation in the potential for agri-environment schemes to deliver ecosystem services and economic benefits to society under these changes. This gave added consideration to enhanced opportunity for recreation and improvements to human health from better air quality. These issues are being further explored for Welsh Government using an Integrated Modelling Platform to model ecosystem services outcomes (including valuation) for policy scenarios at national scale.

2.4. DELIVERING, MANAGING AND MONITORING NATURE-BASED SOLUTIONS

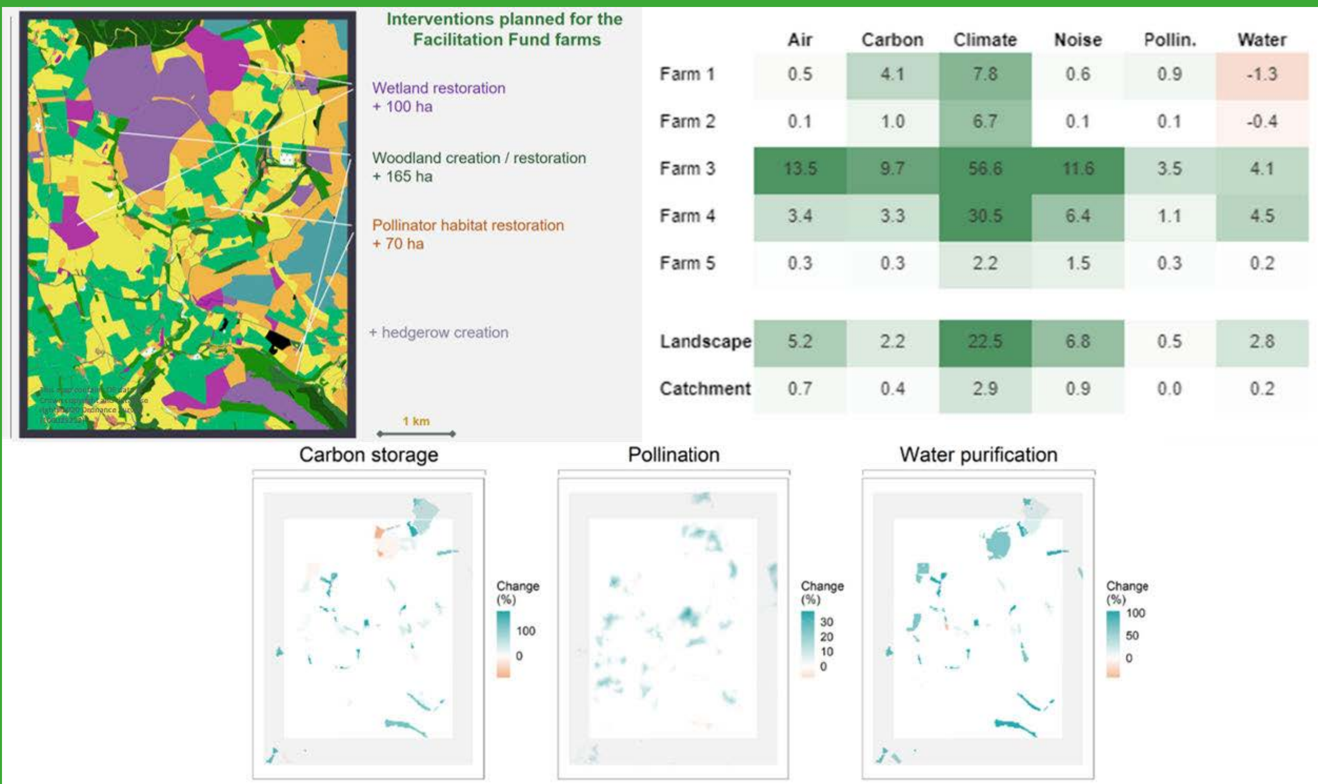
Having identified potential opportunities to deliver NbS to meet societal and environmental challenges, the next step is to evaluate the different options to ensure spatial coherence, equitable delivery and cost-effectiveness. Various evaluation tools exist; these generally compare asset maps before and after interventions, and estimate the change in the capacity for ecosystem service delivery either as a score, a percentage change or a biophysical or monetary value (see Case Study 6). Such approaches also allow scenario analysis to test future policy approaches driven by different planning objectives, e.g. a trade-off between the developers' desire for place making close to the development against the need for large scale investment in flood regulation upstream of the urban conurbations. Approaches that allow assessment of changes at both the site level and across wider geographical boundaries (i.e. ward, local authority) can also inform on how the NbS is contributing to net gain or loss across areas which can inform cases of investment to achieve equitable provision of benefits[10,18,20].

Having identified potential NbS opportunities, these can be prioritised to form a pipeline of investment-ready projects. This paves the way for developing sustainable flows of investment funds. NbS need to be planned and implemented across policy areas (environment, planning, transport, business etc.) and draw on a variety of mechanisms (net gain, local plan policies, nature recovery networks, brownfield registers) to gain the benefits from policy drivers and optimise potential investment streams.

Following implementation, ongoing monitoring and evaluation is needed to evaluate the effectiveness of NbS interventions, and to enable adaptive management (if necessary) in response to change. Projects should include a budget for long term management and monitoring of NbS, and should ensure that maintenance and management staff have appropriate training.

CASE STUDY 6. ENVIRONMENTAL LAND MANAGEMENT SCHEME TEST & TRIAL: MAPPING THE EFFECTS OF NATURE-BASED SOLUTIONS BASED AGRI-ENVIRONMENT INTERVENTIONS IN THE DANE CATCHMENT CHESHIRE

As part of a DEFRA ELMS test and trial in the Dane Catchment, Cheshire, the impact of land-scape scale NbS based agri-environment inter-ventions derived by a local farm advisor were evaluated using EcoservR (see https://ecoservr.github.io/EcoservR/). Changes in ecosystem service due to the interventions were measured at farm, landscape and catchment scale. The approach has been tested with farm advisors and farmers for its use in developing land man-agement plans and could be used to test various options for NbS interventions across the farm and landscape scale[20].



	Air	Carbon	Climate	Noise	Pollin.	Water
Farm 1	0.5	4.1	7.8	0.6	0.9	-1.3
Farm 2	0.1	1.0	6.7	0.1	0.1	-0.4
Farm 3	13.5	9.7	56.6	11.6	3.5	4.1
Farm 4	3.4	3.3	30.5	6.4	1.1	4.5
Farm 5	0.3	0.3	2.2	1.5	0.3	0.2
Landscape	5.2	2.2	22.5	6.8	0.5	2.8
Catchment	0.7	0.4	2.9	0.9	0.0	0.2

Figure 5 – Landscape agri-environment interventions on an asset map of part of the Dane catchment, Cheshire, and resultant change maps and percentage changes in ecosystem services across farms, landscape and catchment extent[20]. Adapted from Angers-Blondin *et al.* (2020)[20].

3. HOW CAN SPATIAL PLANNING POLICY DELIVER BETTER OUTCOMES FOR NATURE-BASED SOLUTIONS?

For NbS to deliver their potential benefits, a strategic spatial planning approach needs to be embedded within wider local and national policies. Here we present three examples at the local and regional level:

- The South Downs Local Plan embeds ecosystem services as one of four core policies that apply to all developments (Case Study 7)
- The Liverpool City region is seeking to embed a Natural Capital Approach into planning and decision making including the Spatial Development Strategy (SDS) and Local Industrial Strategy (Case Study 8)
- The Swansea Green Infrastructure Strategy is using the Green Factor Score approach to mandate inclusion of high-quality green infrastructure into new urban developments (Case Study 9)

At a national level while a spatial strategic planning approach is not fully embedded in policy there are signs of a positive direction of travel.

In **England**, for example, the introduction of mandatory Biodiversity Net Gain and the requirement for Nature Recovery Networks through the Environment Bill and encouragement of Environmental Net Gain in the NPPF Guidance[31] endorses a strategic and spatial approach. The recent Planning White Paper's[32] focus on "digital first" and various mentions of the net gain principle also supports this. The White Paper does however herald a significant shift towards zoning systems where areas are identified for development, regeneration and protection within local plans with codes used to provide standards for approval. This presents both challenges and opportunities for spatial planning within a stronger plan led system.

In **Scotland** there is an emerging National Planning Framework 4 (NPF4)[33] which continues the strong spatial planning approach to development. The November 2020 position statement acknowledging the need to go further in securing positive effects for biodiversity from development, helping to address the global challenge of biodiversity loss in line with a new statutory outcome for NPF4. It also recognises an opportunity space to "Expanding green infrastructure, biodiversity and natural spaces to make our places greener, healthier and more resilient to the impacts of climate change". In this regard, NPF4 will benefit from support in the new Infrastructure Investment Plan for Scotland, which includes nature in its formal definition of infrastructure.

In **Wales** there is a strong framework for spatial planning emerging. The (draft) National Development Framework (NDF)[34] is a new 20-year national spatial strategy, with development plan status. It sets out the Welsh Government's policies on development and land use in a spatial context. The NDF is required under the Planning (Wales) Act 2015 and must be reviewed every five years. Of most relevance is Policy 9 – Resilient Ecological Networks and Green Infrastructure, which aims "to ensure the enhancement of biodiversity, the resilience of ecosystems and the provision of green infrastructure". Under the framework the Welsh Government will identify areas for habitat creation and protection for ecological networks and opportunities where existing and potential green infrastructure could be maximised, requiring the use of NbS. Planning authorities should then include these areas and/or opportunities in their development plan strategies and policies.

CASE STUDY 7. SOUTH DOWNS NATIONAL PARK: DEVELOPING ROBUST SPATIAL PLANNING POLICIES WITHIN WHICH NATURE-BASED SOLUTIONS CAN FLOURISH

The South Downs National Park Authority took a strategic decision to embed nature and ecosystem services at the heart of their Local Plan[35]. Following a series of iterative workshops with planners and the Park Board, they created a policy on ecosystem services (Figure 6) which is one of four core policies that must be met in all development decisions. Developers must detail both the positive and negative impacts of any developments on a specified list of ecosystem services, and must actively seek out ways of enhancing ecosystem services to help secure planning permission, thus framing the NbS narrative as part of a business case. This is supported by mapping to identify ecosystem service priorities and impacts for any potential development location. The policy is underpinned by dedicated guidance for householders and developers, and explicitly addresses viability, trade-offs and net gain potential. It is effective as a negotiation tool to enable planners to explicitly embed biodiversity and wider environmental net gains in developments at any scale, showing how statutory planning policies can provide an important catalyst for the delivery of NbS.

Core Policy SD2: Ecosystem Services

1. Development proposals will be permitted where they have an overall positive impact on the ability of the natural environment to contribute goods and services. This will be achieved through the use of high quality design, and by delivering all opportunities to:
   a) Sustainably manage land and water environments;
   b) Protect and provide more, better and joined up natural habitats;
   c) Conserve water resources and improve water quality;
   d) Manage and mitigate the risk of flooding;
   e) Improve the National Park's resilience to, and mitigation of, climate change;
   f) Increase the ability to store carbon through new planting or other means;
   g) Conserve and enhance soils, use soils sustainably and protect the best and most versatile agricultural land;
   h) Support the sustainable production and use of food, forestry and raw materials;
   i) Reduce levels of pollution;
   j) Improve opportunities for peoples' health and wellbeing; and
   k) Provide opportunities for access to the natural and cultural resources which contribute to the special qualities.
2. Development proposals must be supported by a statement that sets out how the development proposal impacts, both positively and negatively, on ecosystem services.

Figure 6: South Downs National Park Core Policy SD2, on Ecosystem Services. Reproduced from *South Downs Local Plan 2014 - 2033*[35].

CASE STUDY 8. EMBEDDING NATURAL CAPITAL IN THE LIVERPOOL CITY REGION SPATIAL DEVELOPMENT STRATEGY

The Liverpool City Region Combined Authority has proposed a policy in its recent SDS Consultation[36] which seeks to embed a Natural Capital Approach into planning and decision making. This draws on a spatial evidence base, the Liverpool City Region Natural Capital Baseline[18], to prioritise and identify strategic opportunities for Green Infrastructure and habitat provision or improvement, and act as a consistent measure for achieving environmental net gain from new development. The SDS policy is supported by the draft Local Industrial Strategy, which refers to protecting and enhancing Natural Capital as a key strategic objective across a range of policies such as place-making, climate change and air quality, informed by the baseline[37].

CASE STUDY 9. SWANSEA SPONGE CITY: SECURING NATURE-BASED SOLUTIONS IN AN URBAN CITY REGENERATION SCHEME USING THE GREEN SPACE FACTOR (GSF) SET WITHIN WIDER STRATEGIC PLANNING

An innovative green infrastructure strategy was developed for Central Swansea in February 2019, with extensive public and stakeholder consultation[38]. The strategy is designed to support the Local Development Plan and emerging Supplementary Planning Guidance on Green Infrastructure. It contributes to Natural Resources Wales and Swansea Council's duties under the Well-being of Future Generations (Wales) Act 2015 and the Environment (Wales) Act 2016, and supports the delivery of the Statutory Sustainable Drainage (SuDS) Standard 2019 and the Swansea Public Service Board's 'Working with Nature' Objective. The strategy helped reframe the central area of Swansea as a 'sponge city'. It provides an exemplar of cross disciplinary working and agency partnership, championing the ecosystem approach to introduce nature-based solutions including green roofs, rain gardens and pocket parks into a dense urban area requiring redevelopment. The aim was to change the culture of urban development planning and design, and make development control and planning easier for the Local Planning Authority, by using the GSF - a tool for measuring the quantity and multifunctionality of green infrastructure proposed as part of planning applications. The GSF encourages developers to include more and higher quality green infrastructure, such as green roofs and living walls, to meet the required score of 0.3 for predominantly commercial developments and 0.4 for predominantly residential developments. For example, the Biophilic Living, Swansea development (Figure 7) easily meets the required threshold, with a score of 0.6, highlighting how high quality green infrastructre can be factored into urban developments.

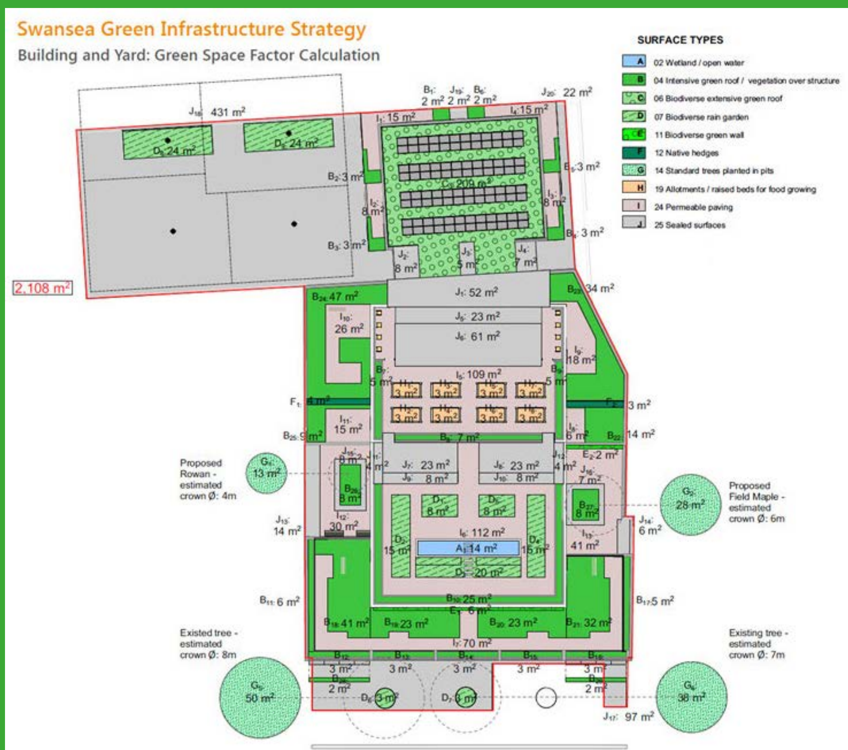


Figure 7: Biophilic Living development, Central Swansea, with a Green Factor Score of 0.6. Consultant: Green Infrastructure Consultancy, CGI image by iCreate, Plan image by Powell Dobson Architects, ©Hacer Developments, reproduced with permission from David Dolman[38].

4. CONCLUSIONS AND RECOMMENDATIONS

In this chapter we have set out a strategic approach to spatial planning to inform good decisions about delivering the right NbS in the right places, illustrated by examples that show how elements of this approach are being implemented throughout the UK. Strategic planning approaches are also beginning to be integrated into wider policy and decision making in several regions. Here we suggest a number of recommendations for policymakers, to ensure such processes become mainstream.

- **Support stakeholder partnerships** to create strategic and coherent plans**.** Stakeholder participation, collaborative action and the community voice are vital in planning NbS to equitably meet multiple needs (Section 2.1). Financial and technical support needs to be provided for LNPs and similar groups (e.g. Catchment Management Partnerships, Farmer Clusters and Neighbourhood Plans) so that they can help deliver a diverse mix of well-planned NbS that optimise synergies and manage trade-offs at landscape scales.
- **Develop and maintain the evidence base to inform a strategic spatial planning approach to NbS.** This requires technical capacity within relevant teams (i.e. local and regional government), access tools for spatial analysis, and freely available spatial natural capital data, including both national level datasets and local data on habitat type, condition and management (Section 2.2). Currently, many key datasets are not freely available (particularly to those outside the public sector), so natural capital maps developed by researchers cannot be shared with all stakeholders. It is important that government continues to develop free access to data, including via support for Ordnance Survey. Key to local data availability is developing a mechanism to fund Local Environmental Records Centres, so that they can continue to manage the volunteers who collect local data, and to enable them to make the habitat and species monitoring data collected freely available where appropriate. Support for the development of citizen science software applications will also play a role here.
- **Invest in approaches and tools for analysing landscape level trade-offs and prioritising NbS.** There is a need to support, develop and test approaches for designing NbS at landscape scale, taking into account trade-offs between different benefits. While approaches are emerging, there is a need to ensure these can assess the benefits and trade-offs for a range of intervention types.
- **Integrate NbS into planning and wider policies**. NbS need to be integrated within wider policies across local and national government bodies and other key organisations (see Section 3).
- **Embed spatial planning which protects** existing habitat networks **and other high value natural capital assets.** It takes many decades to reach peak values for delivering services to people.

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DELIVERING NATURE-BASED SOLUTIONS

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1. CHAPTER SUMMARY

This chapter discusses how nature-based solutions (NbS) can be delivered across the United Kingdom. Section two provides a brief discussion of the need to integrate and coordinate NbS across a range of sectoral policies. It also identifies the kind of mechanisms that have most potential to effectively deliver NbS. Section three discusses the elements that are necessary to design, implement and evaluate NbS, including governance processes, initiatives to provide and share knowledge and build social capital, inspection and enforcement activities, and monitoring. Section four discusses the need to secure long-term funding for NbS, including for the research that is crucial to ensure their effectiveness.

This chapter makes nine key recommendations to help UK governments effectively address the current challenges of the NbS approach and integrate NbS into relevant existing policies, rather than recommending a new standalone NbS policy. Our recommendations to improve future NbS delivery across the UK include:

- **Integrate across all relevant policies and 'mainstream' NbS:** As a relatively new multi-sector approach with both biodiversity and societal objectives, NbS require greater profile and traction in all the policy areas they can benefit.
- **A comprehensive and fit for purpose assessment framework:** An effective NbS assessment framework is required that enables transparent assessments at multiple spatial scales and can be utilised by all key stakeholders. It needs to be able to account for the multiple benefits of the NbS initiative for both nature and climate over time, in line with defined objectives, standards, criteria and metrics.
- **A novel approach to governance:** NbS require a multi-stakeholder governance framework that ensures integration and coordination across all relevant spatial and temporal scales. Such a framework could help overcome existing resource and skill deficits by combining public and private sector input, and should ensure independence of assessments.
- **Facilitation of advice and knowledge exchange:** Methods to share knowledge (including local knowledge) and advice need to be built into the fabric of NbS initiatives. This is especially important when NbS are innovative practices that require new skills. Meaningful collaboration will be key to NbS and a coordinator may be instrumental in this for larger projects.
- **Comprehensive monitoring:** The multi-stakeholder governance framework needs to incorporate carefully designed monitoring systems, with a strong foundation of baseline data, in order to determine if the ambitions of the project are being met. This will require the inclusion of biodiversity and carbon, as well as human wellbeing metrics.
- **Continued refinement to carbon accounting and standards:** More research and data gathering are necessary to improve carbon monitoring, in order to increase reliability and decrease costs. It is also important to ensure an independent examination of carbon accounting.
- **Long-term financial support for NbS initiatives:** This will be required for initiatives and the bodies which deliver them. It will also be important to ensure that research relevant to the design, implementation and monitoring of NbS is adequately funded.

2. POLICIES FOR NATURE-BASED SOLUTIONS

2.1. NATURE-BASED SOLUTIONS BENEFIT A RANGE OF SECTORAL POLICIES

Across the UK and within each of the four nations, no individual policy or strategy exists that solely focuses on NbS and ensures they are delivered in a planned and coordinated way. However, many policies are relying on NbS to enable them to meet their targets. For example, the UK Climate Change Committee's *Land use: Policies for a Net Zero UK* 2020 identifies woodland creation and peatland restoration (amongst others) as key components for reaching a Net Zero emissions target.

The International Union for Conservation of Nature (IUCN) encourages NbS to be considered an 'umbrella concept that covers a whole range of ecosystem-related approaches' and highlights that these approaches mostly pre-date the emergence of NbS[1]. This helps to explain why NbS relevant policies are so fragmented – and the wide range of opportunities for NbS across many sectors for both climate mitigation and adaptation.

If NbS are to be adopted on the scale required to enhance national biodiversity and contribute to climate change mitigation and adaptation, it is vital that NbS are 'mainstreamed' and integrated across all relevant policies, including environmental, health, economic and infrastructure policies and land/marine planning systems. Currently, a barrier to the delivery of NbS is that policies are often developed and delivered in silos.

In addition, where environmental and other policies compete in the same location, the environment is seldom the overriding priority. In contrast, where NbS are utilised effectively, they can align the implementation of diverse policy objectives and deliver benefits across different sectors (e.g., transport, water, agriculture, forestry, energy, and human health). With such demonstrable benefits, there is a greater chance of adoption and successful completion, both from the financial aspect of raising necessary funds but also by directly addressing conflicts and competing priorities.

The recent departure of the UK from the European Union provides an opportune time for addressing some of the issues with delivering NbS across the UK as new policies such as for agriculture, environmental conservation and land use are being developed.

Recommendation: Nature-based solutions should be 'mainstreamed' and integrated across all relevant policies.

2.2. DELIVERY MECHANISMS FOR NATURE-BASED SOLUTIONS

The widespread deployment of NbS will require the coordinated use of a combination of different mechanisms operating as a coherent policy mix. Joined up thinking will be critical to this along with the 'mainstreaming' of NbS across strategies. Two groups of delivery mechanisms will be central to NbS delivery in order to ensure outcomes are achieved at the scales required to effectively contribute to tackling climate change and biodiversity loss. These are: the land use planning system and the use of financial incentives.

Land use planning. The land use planning system is an open, democratically accountable system with a strong legislative underpinning. The importance of spatial planning, as a key component in the delivery of NbS, has been addressed in *Chapter 9: Embedding NbS in Strategic Spatial Planning* which highlights the importance of a strategic spatial planning approach to balance competing demands on land at a landscape scale. This chapter, however, considers how the design of large-scale NbS projects, such as at the landscape or catchment level, requires effective frameworks, assessments and standards to ensure that when interventions are implemented at the local site level, they are properly coordinated and will deliver multiple benefits across sectors. This is not to ignore the value that small scale NbS interventions, such as green roof installations, contribute to tackling the climate change, biodiversity and wellbeing crises nor the importance of empowering and building support for NbS at personal and local levels.

Financial incentives are widely used across the UK to promote environmental land management, tree planting and woodland/forestry management. Land management agreements are already used to promote NbS to climate change and have the potential to be more widely used in future, particularly if the UK administrations take advantage of the current opportunities to redesign their future agricultural payment systems to focus on the delivery of environmental and climate goals. Important financial incentives that can be used to promote NbS include payments to land managers[1], permit/credit markets[2] and green tax incentivises[3]. Conservation covenants[4] also have potential as a mechanism for delivering NbS, complementing financial support for land managers by giving assurance of long-term stability in management. Additionally, dedicated Government funds, such as the £640 million Nature for Climate Fund to restore peatlands and fund tree planting in England, will be instrumental in NbS delivery.

It is worth noting the value for money and returns on expenditure that can be associated with NbS initiatives. For example, the managed realignment of the shoreline at Medmerry, Sussex, cost approximately £28 million but has generated around £90 million in direct economic benefit as well as providing 1,000 times better coastal flooding protection than the previous defence system in the area[2]. Investment in NbS could also form part of a 'green' approach to economic recovery in the wake of COVID-19, through helping to stimulate employment and support economic growth[3,4] (see *Chapter 11: Economic Valuation and Investment Options for Implementing Nature-based Solutions* for further discussion).

Ultimately, no one delivery mechanism provides the answer to securing NbS at the scale required in the future. A mix of different mechanisms is required, appropriate to particular desired benefits, working as part of a coherent package with an extended reach of NbS into other sectors such as infrastructure and water management. As noted above, there is a significant opportunity currently available to all four UK administrations through the redesign of the frameworks for agricultural support as the UK leaves the EU, which provides the potential to reorient public financial support towards positive incentives for land managers to deliver public goods and support NbS.

3. ENABLING NATURE-BASED SOLUTIONS

For NbS to deliver both environmental and socio-economic benefits via the mechanisms described in *section 2*, they need to have clear objectives for both. They also need to be supported by mechanisms for building nature and social capital, and for providing advice and support, backed up by monitoring and regulation.

These mechanisms need to be deployed within an effective framework of governance and adjusted in the light of monitoring and evaluation. The following sections explore these elements in more detail.

[1] Payments to land managers can be publicly funded or funded privately (e.g. water companies that aim to improve water quality and carbon offsetting schemes).
[2] This mechanism delivers environmental benefits though a regulated or voluntary permit or credit market. Examples of environmental credit markets include the Woodland Carbon Code and Peatland Code in the UK, which provide a standard for habitat creation/restoration projects that can be used to verify the amount of carbon sequestered. This can then be used as a basis for trade in carbon credits and is a mechanism to attract carbon funding to support woodland creation or peatland restoration projects.
[3] Green taxes aim to discourage environmentally damaging activities.
[4] A conservation covenant is a voluntary, legally binding private agreement between a landowner and a 'responsible body' (usually a public body or conservation charity).

3.1 GOVERNANCE FOR NATURE-BASED SOLUTION IMPLEMENTATION

The use of NbS to achieve environmental and societal objectives will require good governance[5] at a variety of spatial scales to be effective. They will need to be coordinated at the national (and ideally international) level, may need to be enabled by national legislation and will need to be implemented regionally and/or locally. Governance of implementation can be top-down, where a central or regional body works out the spatial requirements and targets measures appropriately or bottom-up, where sectoral interests (e.g. land and marine managers, communities, responsible bodies) decide for themselves what environmental and societal objectives to pursue and where.

The overarching approach to NbS needs to be coordinated and strategically assessed by UK or devolved administrations (and where appropriate across national borders) but will need to be designed, planned, assessed, and implemented regionally and locally. There is also the need to balance central coordination to meet national policy with empowering local ownership of issues and drawing on local knowledge.

The most appropriate form of governance may vary depending on the local delivery instrument, but a system that can combine elements of the top-down (to help ensure consistency, alignment with national policy priorities and incorporation of scientific evidence and practical experience into action) as well as bottom-up approaches (to account for local conditions, achieve buy-in, equality and social capital) has the potential to combine the best features of both. NbS, therefore, require collaborative governance and a collaborative approach to their planning and implementation[5] involving multiple institutional scales and/or actors. There also needs to be flexibility in how governance arrangements (as well as business models and modes of financing) are developed and implemented[6] to reflect local, and changing, situations. In addition, it will be important to define quantified, measurable targets for nature and for societal outcomes from NbS deployment. These need to accommodate the range in temporal scales associated with NbS initiatives (i.e., some need a long amount of time before being effective).

Recommendation: Nature-based solutions require a multi-stakeholder policy framework that ensures integration and coordination across all relevant spatial and temporal scales. The framework should also include mechanisms for effective assessment at the full spatial range, ensure inclusive participation, co-creation of delivery mechanisms, collaboration, effective monitoring, accountability, enforcement, and transparency.

3.2 ASSESSMENT

A comprehensive NbS assessment framework is an important component to ensuring properly planned and designed NbS initiatives that will deliver the desired multi-benefits. Existing assessment frameworks, such as the Strategic Environmental Assessment Regulations and the Environmental Impact Assessment Regulations, as well as planning systems, should be evaluated and adapted to ensure they are fit for the purpose for assessing NbS initiatives.

Establishing clear objectives for nature and society is a key part of defining and delivering NbS, and is vital in optimising the co-benefits that NbS have the potential to deliver. As identified within some of the habitat-based chapters of this report, without clear objectives for both nature and societal benefits, NbS can end up being poorly planned and designed, resulting in poor outcomes and (at worst) environmental damage. For example, woodland creation on unsuitable habitats such as peatlands, or carbon-rich organo-mineral soils with inappropriate ground preparation and inadequate greenhouse gas assessment can lead to net emissions rather than sequestration of carbon. Inappropriate choice of tree species could also reduce biodiversity. In contrast, well-planned NbS with clear objectives for both climate and nature have great potential to tackle the two defining crises of our age.

[5] In the context of this chapter, the meaning of a governance framework is to provide a system that supports (either through regulation and/or through non-legally binding mechanisms) the collective and coordinated actions across different government departments, organisations and local groups as relevant to achieve the implementation of a well-designed NbS, optimally suited to the location.

The IUCN Global Standard for Nature-based Solutions helps address the risk of adverse outcomes and recommends that NbS actions directly respond to evidence-based assessments of the current state of the ecosystem and prevailing drivers of degradation and loss as well as options for net improvements. The baseline assessment needs to be broad enough to characterise the ecological state, making use of both local knowledge and scientific understanding where possible[7]. It also needs to be comprehensive enough to allow for meaningful monitoring and evaluation of the NbS initiative over time (see *section 3.4*).

Finally, given the multi-sector approach of NbS, strategic and detailed assessments will require professional and specialist knowledge and input (in addition to incorporating local and non-specialist knowledge). This will require an increase in national capacity for this sort of work in both public and private sectors. An appropriate multi-stakeholder governance framework (as further discussed in *section 3.1*) can potentially help to make best use of resource and skills by combining facilities of the public and private sectors.

Recommendation: An effective nature-based solutions assessment framework should be adopted that enables transparent assessments for nature and society at multiple spatial scales, and can be utilised by all key stakeholders. It should also facilitate the gathering of baseline data in order to enable monitoring, assessment and comparison of the multiple values and benefits of the NbS initiative over time, in line with defined standards, criteria and metrics, such as the Peatland Code and Woodland Carbon Code.

3.3 KNOWLEDGE AND SKILLS

It is important that all those implementing the mechanism have the necessary knowledge and skills to properly implement nature-based solutions and are motivated to do so. A series of mechanisms that can help achieve this are described below.

Advice and information. Providing sufficient advice and information is critical when implementing novel nature conservation tools such as NbS. Understanding the different benefits provided by NbS will be important to ensure buy in and a wide uptake.

Collaboration. NbS initiatives should empower collaborative management of land/marine/cityscapes that ensure the right actions are undertaken in the right place through using local knowledge, aligning to local concerns and needs, as well as through including any marginalised voices. NbS can also be the vehicle to bring frequently disconnected actors, sectors, and government institutions together, all in pursuit of a common goal to increase landscape resilience[8] to climate change, improve ecosystem health and human wellbeing. Current governance frameworks that implement NbS do not effectively support collaboration[9].

Meaningful collaboration that is accountable, inclusive, and transparent will help partnerships thrive and continue to function into the future[10], providing the long-term support for NbS projects as required. In addition, collaboration among all the involved stakeholders will decrease litigation and conflict, increase capacity to accomplish work[10], help address trade-offs and ensure a higher likelihood of implementation[6].

Knowledge exchange. Experience from evaluating agri-environment scheme implementation found a positive correlation between incorporating the agreement holder's knowledge and achieving environmental outcomes[11,12]. Platforms to integrate locally specific knowledge to increase the ecological understanding of the landscape and local sites need to be developed.

Coordination. A project coordinator can be an effective addition for NbS delivery (particularly at the landscape scale) to ensure collaboration, coordination and communication between multiple stakeholders and the multi-level governance structure. This may require funding[13]. However, in other situations, such as working with individual land managers, a trusted advisor might be the more appropriate approach. Southern *et al.* (2011) identified the need for a coordinator to help form key partnerships, with a long-term stakeholder driven vision and address the mix of policies, institutions, and delivery mechanisms[9].

Coordinators can also liaise with government and other bodies to arrange support payments, monitoring, training, information exchange and other aspects of the land/marine/city-scape management.

Recommendation: Methods and platforms to facilitate advice and knowledge exchange (local knowledge is key) need to be built into the fabric of NbS initiatives. This is especially important when NbS are innovative practices that require new skills. Meaningful collaboration helps initiation and longevity of NbS projects and reduces potential conflict. A coordinator can be instrumental in this for larger projects.

3.4 MONITORING AND EVALUATION

Monitoring and evaluation are vital parts of project delivery. Without them it is not possible to know whether a mechanism is effective in practice and to make informed decisions about future policy.

The IUCN Global Standard for NbS recommends that clear and measurable outcomes for both biodiversity conservation and climate change response are identified, benchmarked and periodically assessed[6]. Monitoring will be needed to assess the effectiveness of measures at a particular NbS site, ensuring the specific intended outcomes for both nature and society are being met, in addition to allowing for adjustments to be made if the intended outcomes are not progressing as planned or not being achieved. Monitoring should also include assessments of unintended consequences, both positive and adverse, on nature[6] and societal benefits, and needs to account for natural changes (for example, ecological succession) and other changes (such as different weather patterns resulting from climate change, or societal changes). Measuring what constitutes success in climate change adaptation for ecosystems needs particularly careful attention[14].

Site-level monitoring will need appropriate resourcing and to be incorporated into and analysed at a broader level, such as at the catchment level, to evaluate the effectiveness of the delivery mechanism as a whole. Evaluating the full extent of benefits delivered within the wider landscape context is particularly important for ensuring appropriate results-based payments associated with a NbS project.

Outputs should be easy to monitor so they can provide early feedback on the performance of a policy mechanism. Crucially both result and outcome monitoring will need good baseline data. Results require site-based monitoring and outcomes may be informed by national programmes of sample monitoring and/or surveillance. Although the data takes time and resource to collect, monitoring of results and outcomes will be essential for evaluating the effectiveness of policy mechanisms delivering NbS.

The monitoring and evaluation of a delivery mechanisms environmental and societal outcomes should ideally be accompanied by economic and social evaluations of that mechanism to build up a holistic picture of its effectiveness, value for money and sustainability[15].

It is important to note that NbS can have greatly varied timescales for delivering their benefits. Some might be immediately effective; some may take years and others decades. This temporal variation is something that needs to be addressed in terms of monitoring, evaluating, and funding.

Collaboration and participation can be the key components of the monitoring and evaluation framework. For example, the EU H2020 NAture Insurance value: Assessment and Demonstration (NAIAD) project found that the development and deployment of a 'community-based monitoring system' enhanced both the knowledge and participation of local stakeholders[6,16]. Such community participation may also enhance people's connectedness and engagement with nature, which in turn could help increase the likelihood of NbS implementation.

As a relatively new approach to nature and climate change it may also be useful to monitor the uptake of NbS schemes. Assessing the extent of NbS delivery for a range of key objectives for biodiversity and climate change mitigation and adaptation would track progress and inform the development of policy and funding to fulfil the potential of NbS.

Recommendation: The assessment of NbS requires carefully designed monitoring systems, with a strong foundation of baseline data, to determine if objectives are being met.

Monitoring and measuring carbon flux. Carbon accounting is a field that is still under development, with a number of methodological challenges and data gaps. At present, some elements (e.g. carbon stored in biomass above ground) are easier to measure than others (e.g. changes in the carbon content of the soil[17]). In the next few years, the ongoing effort on carbon accounting methodologies and data gathering for carbon accounting will allow us to estimate, with increasing precision, changes in emissions and carbon storage resulting from NbS projects, while reducing the costs of monitoring.

In general, there are several difficulties in measuring the realised climate change mitigation benefit from different NbS and comparing the outcomes across different temporal and spatial scales and habitat types[11]. For managed NbS, the net carbon balance depends on the goals, costs implementation and end-of-life phases (e.g. if timber is used for building materials or becomes paper) and, whilst there may be promising estimates regarding carbon sequestration, the net balance will be impacted by the materials used and type of management (e.g. fossil fuel free)[18].

The appropriate frequency of repeat monitoring needs to be defined, funded and delivered based on the NbS project aims. Given the relative novelty of delivering NbS at scale, an adaptive management approach will be necessary[19]. (Carbon credits and the peatlands and woodland codes are discussed in *Chapter 11: Economic Valuation and Investment Options for Implementing Nature-based Solutions*).

It is important to note that, as recommended by the Climate Change Committee, an emission governance system should be transparent and should ensure robust monitoring and verification through independent auditing'[20].

Recommendation: The approach to carbon accounting needs to be refined, as NbS will form an increasing part of carbon reduction towards Net Zero goals. Systematic and independent verification of carbon accounting will help to ensure trust among the relevant stakeholders.

3.5 FUNDING

In order to mainstream the implementation of NbS across multiple relevant policies, it is important that governments earmark public funding for NbS, as well as provide support and guidance for funding instruments.

Funding and investment support need to be guaranteed for longer timeframes than is currently normal for environmental management, as it can take decades rather than years before some NbS become effective and during this period management and monitoring may be required. For NbS that require a long time to provide the desired outcomes, the best option is generally to link the payment to a set of pre-defined management actions that are designed to result in the desired outcomes. Conversely, for NbS whose outcomes occur faster and are more easily measurable, the payment can be linked to the result of the incentivised action, such as e.g. in result-based agri-environment schemes[6].

Successful financing of NbS will likely come from a diverse number of public and private sources. It is, therefore, important to gather the evidence on the cost-effectiveness of NbS so that this can be used to help trigger both public and private finance and investments mechanisms, and to include NbS as a means of delivering societal benefits from current funding streams. Financing of NbS is a topic covered in detail in *Chapter 11*.

Funding local delivery of NbS. Resourcing of government bodies such as Natural England, National Parks, NatureScot, Scottish Environmental Protection Agency, Natural Resources Wales and Northern Ireland's Department for Agriculture, Environment and Rural Affairs has been declining over recent years[21,22,23,24]. Many of these bodies play a central role in planning, assessing, advising, providing support, regulating, and helping form partnerships, which are all key components for the successful delivery of NbS projects.

Volunteer groups and NGOs also provide an important avenue for locally delivering NbS across all urban, peri-urban and rural settings. Yet financial support, particularly from government, for these important networks and organisations has been declining in recent years (coinciding with the cuts to government departments).

[6] See some examples here: https://www.gov.uk/government/publications/results-based-agri-environment-payment-scheme-rbaps-pilot-study-in-england

Without guaranteed long-term support, be that of payment mechanisms through policies such as agri-environment schemes for site specific NbS measures, or of organisations, the local implementation of NbS risks being undermined.

Funding research. The use of NbS to reach climate and biodiversity objectives is still an innovative approach, and therefore research is still needed to ensure the design, implementation and monitoring of NbS is carried out in an increasingly cost-effective way. To date research funding for NbS projects has tended to come via EU streams such as Horizon 2020. It will therefore be critical to ensure that in future the same level of funding is provided across the UK national budgets after the current arrangement that allows UK university access to Horizon Europe (the successor of Horizon 2020) ends.

Recommendation: Securing long-term financial support for NbS initiatives and the bodies which deliver them will be necessary for the UK to tackle our climate change, biodiversity and wellbeing crises. It will also be important to ensure that research relevant to the design, implementation and monitoring of NbS is adequately funded.

4. CONCLUSION

As identified in this chapter, there are number of steps that need to be taken to ensure the successful and long-term implementation of NbS across the UK's four nations.

Given the multiple actors that need to be involved in the governance of NbS, the challenges of working across policy silos as well as generating effective partnerships, we recommend that **approaches to NbS should be included across policy both within devolved administrations and, as far as possible, between them. The latter might be facilitated by a working group or groups to assess both opportunities and existing policy and governance frameworks to deliver NbS.**

In addition, we recommend the need for initial assessments to be carried out to identify the existing gaps, shortfalls, strengths, and best practice of NbS delivery across the four UK nations[7]. The results from the initial assessment should then help address the challenges identified within this report. Including, for example, designing an approach to NbS delivery that:

- Identifies the range of opportunities for NbS for climate change adaptation and mitigation as well as biodiversity enhancement.
- Incorporates these opportunities across all relevant policies.
- Defines multi-stakeholder objectives and enables adaptative governance structures.
- Engages communities and stakeholders to enable collaborative decision-making.
- Develops governance processes and forms of investment that are appropriate to the competing demands for land use and long-term delivery of NbS benefits.
- Develops monitoring standards and frameworks to assess the effectiveness of the NbS for nature enhancement and societal benefits, including carbon sequestration (particularly within a changing climate) and adaptation to climate change.
- Develops standard methodologies for assessing the benefits delivered by NbS.

We recommend **commissioning an analysis of NbS interventions to ascertain which are the most effective NbS to implement and where, in order to provide optimal benefits for biodiversity and climate change together with other benefits for people**.

NbS is an evolving approach with great potential to benefit both nature and people. With the UK being in a phase of (re)drafting policies and programmes since leaving the EU, it is an opportune time to deliver the frameworks and plans needed to underpin the successful delivery of NbS. As showcased throughout this report, the benefits and challenges of NbS are many and varied, and require a multi-sectoral, multi-governance approach with

[7] This has in part been addressed by the discussion paper from the Climate Change Interest Groups of the European Network of the Heads of Environment Protection Agencies (EPA Network) and Heads of European Nature Conservation Agencies (ENCA) on the Recommendations for overcoming barriers to mainstreaming the delivery of Nature-based Solutions. https://epanet.eea.europa.eu/reports-letters/reports-and-letters/nature-based-solutions_interest-group-climate-change-and-adaptation.pdf/view

true and comprehensive collaboration throughout all stages of NbS design and implementation. This poses a policy challenge. However, with the right frameworks in place to underpin NbS, the much-needed ambitious goals of the NbS approach can be achieved. Long-term policies, goals and government commitments are necessary to support long-term investment, research, monitoring of functionality of NbS, and their deliverability. This would also help safeguard NbS initiatives from unexpected shifts in political support[11] and ensure continuity of NbS projects to deliver benefits across the timescales required.

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ECONOMIC VALUATION AND INVESTMENT OPTIONS FOR IMPLEMENTING NATURE-BASED SOLUTIONS

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1. KEY POINTS

1. NbS provide multiple benefits related to climate mitigation and adaptation, biodiversity conservation and enhancement and wellbeing. Some of these ecosystem services can be valued monetarily to inform decision making, while others can be assessed in quantitative and qualitative terms.
2. Because of the complexities of valuing all the ecosystem service flows and benefits over time and space, qualitative approaches to recognise value where it cannot be quantified can help inform decisions. Currently valuation of NbS is partial which may lead to undervaluation.
3. NbS are effective mechanisms to create jobs and contribute to green recovery following the economic crisis caused by the Covid-19 pandemic.
4. Governments are, and will remain, key financial investors in natural assets and their sustainable use, given the societal benefits of such investments.
5. However, the private sector can play an important role in complementing public investments in NbS. For private finance to occur, NbS must be of appropriate scale and provide sufficient return on private investment.
   - Lack of evidence of financial return is a major barrier to private investors. For this reason, it is important to create and disseminate information on the profitability of NbS for private investors.
   - Innovative funding mechanisms can be used to encourage private investment, including payments for ecosystem services, catchment markets, habitat banks, regional aggregation brokers and debt instruments.
   - Changes to regulation also have the potential to encourage private investment in NbS, for example, by requiring consideration of the use of NbS for flood mitigation, biodiversity no net-loss / net gain regulations, or make green roofs compulsory in new buildings.
   - The role of private investment in terms of environmental outcomes and cost-effectiveness should be monitored and evaluated.
6. The revenues generated from fiscal instruments like taxes, fees and charges can be used to finance NbS, thereby representing an additional financial source.

2. INTRODUCTION

There is considerable recent work on economic analysis of and financial solutions to climate change and biodiversity loss, many of which focus on overconsumption of natural resources and ways to reduce this. Approaches to economic reform range from increased taxation through to 'degrowth' strategies[1,2,3,4,5,6]. Nature-based solutions (NbS) sit somewhat apart from these discussions over economic reform, utilising different processes and policies for protecting biodiversity and reducing the net accumulation of greenhouse gases (GHG)s in the environment[7]. Nevertheless, implementation of NbS requires investment, for example, for necessary land acquisition, labour related to creation or maintenance of NbS and the costs of integrating NbS into infrastructure. This chapter is written in light of the Dasgupta review[8] and other recent work, to provide an overview of the valuation of NbS and the different financial mechanisms available for its establishment and long-term maintenance.

3. VALUING THE BENEFITS OF NATURE-BASED SOLUTIONS

Society and the economy derive value from nature through the provision of natural resources, the regulation of ecosystem processes (e.g. carbon and nutrient cycles) and the contribution to human health and wellbeing.

The ecosystem service framework, which describes and quantifies the benefits from nature, is a useful framework for economic valuation[8,9]. This approach can be successfully applied to NbS. For example, a study of river restoration in Europe found net social economic benefits over unrestored rivers of €1,400 ± 600 per hectare per year associated with an increase in cultural and regulating services (including carbon sequestration), while provisioning services remained the same[10]. However, the economic valuation of nature and ecology is a complex process, and some services are difficult to value. Most valuations undertaken are therefore only partial and do not capture the full range of benefits to society. Contingent valuation methods traditionally used, such as willingness to pay, are known to undervalue ecosystems. This suggests that our current best estimates to value NbS are likely an undervaluation[11]. Other methods to estimate value derived from NbS include calculating avoided costs resulting from a solution and have reasonable precision[11]. Carbon offsetting can also provide market level detail to the valuation of mitigation benefits of NbS[12]. However, as seen throughout this report, carbon sequestration is highly variable, and calculation methods may not be fully comparable across different habitats. As such, more work is needed before accurate economic values for carbon sequestration can be provided. The recent Dasgupta review has focussed on the economics of biodiversity, highlighting the importance of valuation to ensure nature is captured in all decision making, while recognising that valuing biodiversity is likely to be imperfect and partial[8].

A large advantage of NbS is that they provide co-benefits and multiple ecosystem services[13]. These services may be provided globally and/or locally, for example carbon sequestration can have global benefits, whilst improved water quality may provide a local benefit. In addition, time scales over which ecosystem services are derived may vary. For example, a benefit of urban greening can be improved air quality, which may take many years to produce financial savings to the healthcare system[14]. These many factors increase the complexity of valuing NbS, but also highlight that even when valuation is imperfect and partial, NbS often provide good value for money for society due to the multiple benefits produced.

The current report provides many examples of the multiple benefits of NbS, including areas where valuation figures are attributed to different benefits. Full economic valuation of NbS is limited, but in general benefits outweigh the costs[8]. H M Treasury's 'Green Book'[15] sets out approaches to evaluation and appraisal of policies, programmes and projects to include natural capital and ecosystem services to enable the inclusion of these values in in decisions about public resources, although recent evidence suggests the approach is rarely achieved[8].

3.1. VALUE OF NATURE-BASED SOLUTIONS AS A RESPONSE TO THE ECONOMIC CRISIS

Investment in NbS could form an effective part of a "green" approach to economic recovery in the wake of the economic crisis resulting from Covid-19, by helping to stimulate employment in the short term and support economic growth in the medium term[16,17]. Jobs can involve little training or require little other capital investment and can provide good returns on investment. For instance, it was estimated that 7-40 jobs are created per $1 million invested in environmental restoration in the United States of America (US)[18] and the American Recovery and Reinvestment Act of 2009 created an average of 17 jobs for every million dollars spent on restoring coastal habitat, which was much higher than traditional industries such as coal, gas, and nuclear energy generation[19].

NbS can also have a direct impact on consumer behaviour, helping to stimulate expenditure[20]. Hedonic pricing methods, which capture consumers' willingness to pay for perceived environmental differences that add or detract from the value of assets, have shown that street trees on a high street can increase consumers' willingness to spend by 10-50%[20] and that public green spaces boost house prices, with detached houses attracting a 1.9% premium if they are within 100 metres of a public green space (although other forms of housing, such as flats have a lower premium)[21]. In addition, studies have shown that high-quality green spaces can build a good business image and improve reputation, encouraging inward investment and employment in an area[20].

To highlight the economic and 'green recovery' credentials of NbS in the UK, a recent report from the RSPB has estimated that investing in peatlands as an NbS will have a cost-benefit ratio of 1:4.6 and create 112,000 job years of employment over the next 100 years, while woodland figures are slightly lower (1:2.8 cost:benefit, 7,500 temporary jobs and an additional 1,800 job years over a 100-year period)[22]. Other habitats are less certain. Although these figures are an acknowledged undervaluation of full ecosystem service benefits, it is clear that NbS can provide net economic benefit and aid with immediate and long-term employment prospects.

4. INVESTMENT IN NATURE-BASED SOLUTIONS

Despite growing opportunities for private investment most funding for NbS comes from public money, either directly or through subsidies. For example, the revenue generated from fiscal instruments like taxes, fees and charges can be channelled into managing, maintaining, and restoring NbS[23]. It is estimated that almost 75% of funding is public within urban settings in Europe[24]. Research into sustainable development and climate funding has indicated that state funding is often the most effective solution, both in terms of outcomes and cost-effectiveness[25]. However, pressures on public spending and government debt are high following the Covid-19 pandemic, meaning public funding may be limited.

The financial system has the potential to significantly increase the funding available for NbS and complement public sources of financing. Nevertheless, many of the finance mechanisms required to implement NbS at larger scales are relatively new or are still being developed, meaning investment, especially from the private sector, remains low[26]. There is a large mismatch in terms of apparent funding (that is predicted to be available) for sustainable development and climate projects from private investment compared to actual funding[25], which needs to be considered when establishing the potential for private investment. Specifically with regard to NbS, it is necessary to consider longer-term management and maintenance beyond the initial capital investment[24].

Both public and private financial actors have important roles to play to ensure there are increasing financial flows invested in NbS. There are a range of mechanisms through which public and private finance can support NbS including nature positive subsidies, taxes, payments for ecosystem services (PES, see Box 2) and offsetting programmes amongst others. There are opportunities to increase green finance through initiatives such as blended finance, where public money is invested alongside private finance to reduce the risk of investment for private actors. Recent work on protected area governance has highlighted the requirement for multi-level stakeholders, which can include local communities, industry and the state working together[27]. In the right conditions and with the right regulations and governance structures in place, co-funded NbS may provide optimal benefits and-cost effectiveness.

4.1. NATURE-RELATED FINANCIAL RISKS

Both public and private finance actors are subject to a range of nature-related risks, for example loss of ecosystem goods and services that support supply chains, risks to infrastructure from environmental degradation (such as flooding) or reputational/legal risks resulting from damaging natural assets (see Figure 1). Understanding, reporting and directing funds to addressing these nature-related risks by finance actors could unlock greater financial flows into conservation and restoration of ecosystems and NbS[28]. The recently formed Task Force on Nature-related Financial Disclosures – which aims to build awareness and capacity on nature dependencies, impacts, and financial risks among financial institutions – indicates a growing understanding of this area and is encouraging[29].

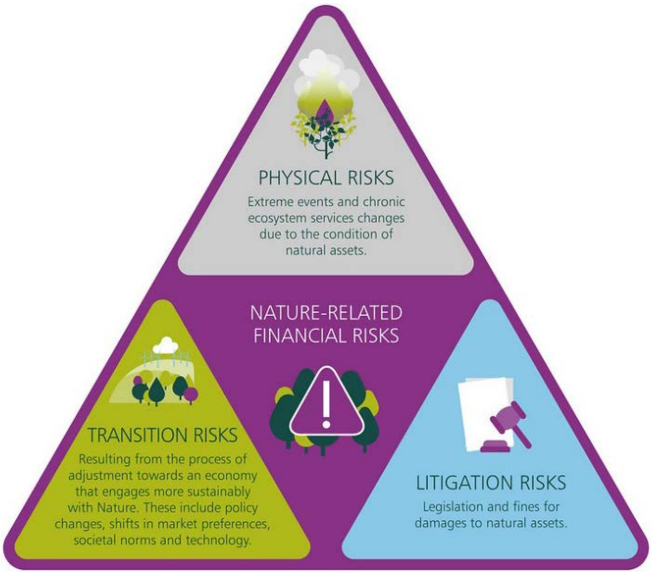


Figure 1. Nature-related finance risks. Figure taken from The Dasgupta Review[8] under Creative Commons licence CCBY2.0

4.2. OVERCOMING BARRIERS TO PRIVATE INVESTMENT

4.2.1. SCALE AND UNCERTAINTY

Barriers to high levels of investment in NbS from the private sector revolve around the scale, transparency and certainty of projects[26]. In general, small NbS projects are less attractive to major investors[26] and the return on investment is often not as clear (beyond the small-scale net gain examples) as for other green investments, such as sustainable transport or renewable energy[30]. As a result, investors tend to favour the implementation of engineering solutions instead of NbS.

Overcoming this uncertainty will require building confidence in NbS as an investment opportunity. This will require evidence of successful delivery at both geographic and investment scales[26]. This includes, for example, disseminating information on NbS projects that can provide and successfully sell multiple co-benefits, having a sufficient pipeline of projects available for investors and having enough certainty for experts to assess the asset class and risks[26].

Directing funding to address research gaps can also help increase confidence in investing in NbS. Areas requiring further research include:

- Generating concrete data and evidence that is in the right form for investors and demonstrate the cost-effectiveness of NbS, as well as showcasing the solutions and benefits ecosystems have to offer[14,31].
- Developing a comprehensive understanding of the nature and scale of NbS benefits in different contexts and modes of implementation. Quantification of at least part of these benefits in monetary terms will be valuable for developing business cases and models[14].
- Trialling and evaluating the development of business cases and models for the implementation of NbS projects[14].
- Developing a clear and consistent set of metrics that can be used to track progress of NbS projects and measure success against specified targets, and ensuring that they are tested for wider applicability and agreed[32].

4.2.2. MECHANISMS AND INCENTIVES

Another barrier to increased private investments in NbS is a lack of coherence between regulatory processes, public funding mechanisms and incentives[26]. For private investment in NbS, corporate social responsibility may fall at one end of the spectrum of investment, requiring little or no return on investment directly[26] and compliance with regulations (such as net gain or net zero emissions) is at the other end [26], generally causing additional costs for business and industry. Other types of private investment include those made to obtain a financial return, as well as acknowledgment of the opportunities for investment in NbS to provide economic benefits by securing high quality natural resources. For example, payments of private mineral water companies to farmers in exchange for management practices that ensure clean water[33]. These different types of private investment require effective mechanisms, regulations and incentives in order to be encouraged.

A recent report by the European Commission highlighted the following as mechanisms to encourage private investment in NbS[14]:

- Encouraging development and greater use of financial instruments such as green bonds and blended finance for NbS (see Box 2 for further details).
- Adopting regulatory requirements that embed NbS in decision-making, such as a requirement to demonstrate that NbS options were explored in decision-making on flood mitigation measures, urban biodiversity no net-loss / net gain-regulations, or compulsory green roofs in new buildings.
- Developing governance mechanisms that allow for coordinated funding of NbS.
- Developing and applying knowledge tools that offer indicators, evidence, transparency and monitoring of NbS.
- Actively engaging the (re-)insurance sector as an option to reduce societies' vulnerability to natural hazards and protect ecosystem services through improving disaster risk reduction and loss prevention.
- Increasing the cost effectiveness of NbS investments by integrating them into planned infrastructure and real estate projects.

Another mechanism which has been proposed by business groups is the provision of environmental credits from investment in NbS (for example, habitat banks discussed further in Box 2)[26]. These credits can then be 'offset' elsewhere, for example against construction projects. Care would be needed to ensure positive environmental outcomes of such a scheme, however, it could be a big improvement for wildlife and nature compared to species relocation schemes, which generally have low success rates[34,35].

It should be noted that, in most cases, private investment in NbS is contingent on co-funding from government sources in the form of tax breaks, subsidies, grants or other funding mechanisms. Environmental subsidies can play a key role in financing NbS, for example subsidies for forest management and reforestation, organic and regenerative agriculture, land management and biodiversity conservation. In addition, the role of private investment in terms of environmental outcomes and cost-effectiveness should be monitored and evaluated over time.

BOX 1: POTENTIAL FUNDING FOR NBS – THE SHARED PROSPERITY FUND

As a member of the EU, the UK received structural funding of approximately £2.1. billion per year. Now that this funding is no longer received, the UK Government pledged to set up a Shared Prosperity Fund to replace it. Very few details on the operation of the Fund had been published at the time of writing, although some were released as part of the 2020 Spending Review[36], which made it clear that the emphasis of the Fund was to operate at the UK level. This has created uncertainty as to where replacement funding will come from and what the allocations may be.

As EU structural funding were of relevance to NbS (see an example in the Case Study below), uncertainty around how this gap will be filled may impact the potential for NbS development. In addition, changes to Structural Funds often take time for investors to adapt to, and without complete clarity the uncertainty and risks to investors could prevent private investment and finance in NbS initiatives. It is expected that the investment framework governing the Fund will be announced in spring 2021, and that information will be provided about the share of the Fund that will be allocated to the places 'most in need'[36]. Given the cross-sector nature of NbS (health, environment, and economy for example) this could bode well for funding access.

Until more detail is known, it is hard to predict the impact this important fund will have for financing NbS.

BOX 2: INNOVATIVE FUNDING MECHANISMS

Paired alongside existing forms of funding from government or local authority budget allocations, philanthropic grants, corporate and individual donations, private investment can support the creation of a long-term sustainable funding base for NbS[37]. However, at present, appetite to invest in NbS by the private sector is limited compared to investment received by the public sector, despite growing interest from the financial sector in green bonds and environmental, social and governance investments[14].

Accelerating private investment in NbS will require significant public funding for project development, aggregation and market development. Public funding will need to de-risk private investment until markets for the full range of environmental services are established, and NbS are a familiar asset class for private investment and finance, in addition to business models for market development being well established[26]. Innovative funding mechanisms to enable private investment in NbS are discussed below.

Innovative Funding Mechanisms for Encouraging Private Investment

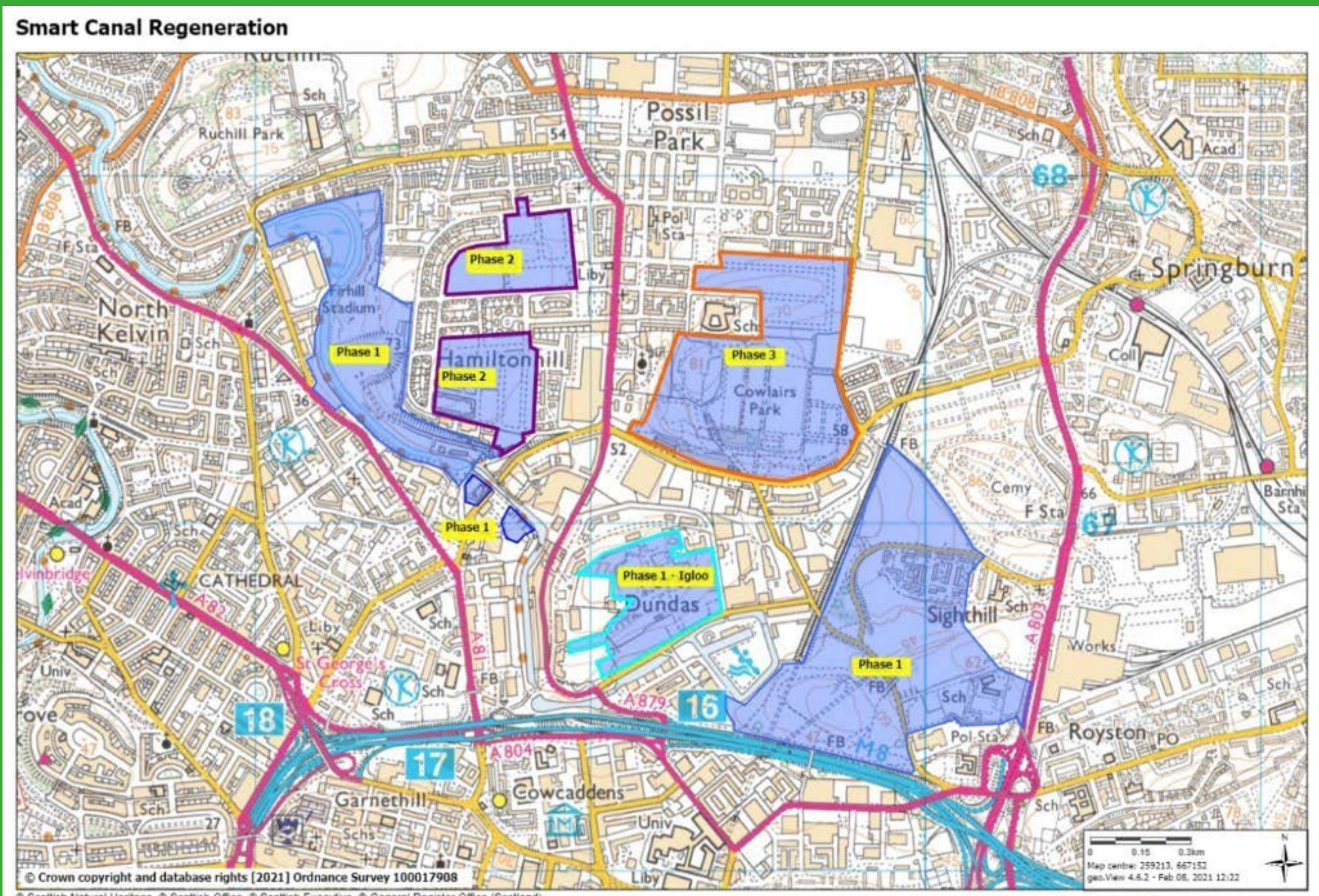
- **PES schemes** are market-based mechanisms which involve payments to the managers of land or other natural resources in exchange for the provision of specified ecosystem services[38]. Payments are made by the beneficiaries of the services, which may include individuals, communities, businesses or governments. In order for schemes to work, they must represent a win for both buyers and sellers and it is critical to put safeguards in place to prevent unintended consequences, such as creating perverse incentives. For example, land managers paid to sequester carbon may be incentivised to plant non-native tree species that sequester carbon at a higher rate than native species, but may have destructive biodiversity impacts (see Chapter 1). To be successful, schemes will require an assessment of the risks, opportunities and unintended consequences, as well as ongoing monitoring, evaluation and audit[39]. An example of a successful PES scheme is the Scottish Rural Development program Agri-Environment and Climate Scheme[40].
- **Catchment markets** are markets where land managers sell multiple ecosystem services produced in a catchment area (e.g. nutrient and biodiversity credits), to organisations that want to offset their environmental impacts[26]. Catchment markets allow land managers to potentially generate more revenues than traditional funding opportunities, because they can sell different environmental credits

to a variety of buyers interested in different types of ecosystem services.

- **Habitat banks** involve investing in projects that generate biodiversity benefits in order to obtain biodiversity credits that can be used to offset environmental impacts. A marketplace is established where developers can purchase the biodiversity credits they need to meet planning approval conditions. Private investment opportunities include initial funding to establish the habitat banks with return paid for by the sale of credits and purchasing the rights to sell biodiversity credits[26].
- **Regional aggregation brokers** bring together businesses, government and communities to agree on challenges facing regions and agree on priorities and opportunities to address these challenges. This can involve developing consortia to deliver specific nature-based projects. Investment opportunities include lending to project proponents or directly investing in on-ground projects[26].
- **Green bonds** are fixed-income instruments used specifically to raise money for climate and environmental projects. They are typically structured in the same way as investment grade (or low risk) bonds in order to maintain low levels of risk and therefore encourage investor confidence. However, green include a "use of proceeds" clause that states that the financing will be used for green investments (including NbS)[41].

FINANCING NATURE-BASED SOLUTIONS – A CASE STUDY: SMART CANAL REGENERATION, NORTH GLASGOW

The Smart Canal is a phased programme using NbS to regenerate areas in the north of Glasgow, and 2021 is approximately halfway through the programme. The area ranks among the lowest in Scotland according to multiple deprivation indicators.



Blended Capital Finance

Public (United Kingdom)	City Deal, Vacant & Derelict Land Fund, Regeneration and Capital Grant Fund, NHS Scotland, Sustrans Scotland
Public (European)	Green Infrastructure Fund (European Regional Development Fund)
Private Finance	Bigg Regeneration
Third Sector	Housing Association private sales

The amount of capital funding of the different financing streams ranged from £100,000 to >£66 million. The inclusion of public funding reduced the risk to the private investor in investing in an innovative method of managing storm water.

Stacked Finance

The project has a number of environmental and social benefits. Firstly, the cost of the project amounted to approximately £10 million, whereas the cost of a comparable grey infrastructure would have costed c.£40 million and may not have received funding. The NbS provided by the project are not only far cheaper, but they are also enabling large scale investment in an otherwise derelict area, with a wider range of co-benefits. For example, the Claypits Local Nature Reserve, which is included in the project, is a green space that can be used for recreation, but also includes a large attenuation basin and habitat for five species of herptiles. In addition, the NbS approach adopted by the project saves c.2,000 tonnes of carbon dioxide equivalent (t.CO_{2eq}) during construction, and c.500 t.CO_{2eq} per annum during the design life of the sustainable drainage systems (SuDS). Moreover, the project creates safe travel routes, with the potential for better health outcomes and reduced CO_2 emissions from commuting. Other positive environmental outcomes include daylighting of streams, and creation of new wetlands.

Funders have different motivations to invest in the project, but all their objectives can be linked to an inner-city regeneration agenda in response to a changing climate. In particular:

- There is a shortage of affordable housing in Glasgow. The combined sewer system is already at capacity, and climate change is predicted to result in more frequent extreme rainfall events. The Green Infrastructure Fund neither funds housing nor grey infrastructure to solve these problems, but it did fund the "Smart Canal Regeneration" project because it was a NbS.
- Poor access to good quality greenspace has a negative impact on health and well-being, which in turn impacts on employment chances. NHS Scotland funded a link path between the local health centre and the Claypits local nature reserve to enable green prescribing (i.e. medical advice to be physically active outside).
- Sustrans (a UK charity that aims to promote walking and cycling) was able to fund a bridge across a canal, enabling easier green prescribing.

Top Down and Bottom Up

The project has both top-down policy support because it ensures the regeneration of vacant and derelict land and bottom-up support from the local community because of its positive impacts related to urban regeneration and access to better greenspace. A key part of the success of the project has been the various master-planning exercises with the local community, followed up by continued involvement of all the relevant stakeholders, including the construction company.

Mixed Governance

Public maintenance of assets is under financial strain and is likely to remain so. Enabling the local community to influence and manage the local greenspaces relieves some of that strain and increases a sense of ownership. This is happening particularly in the Firhill and Hamiltonhill areas.

Benefits

Glasgow Caledonian University led a long-term study into the impacts of regeneration of the Forth & Clyde Canal. The study showed that after 20 years of regeneration there had been an annual 3% improvement in life expectancy within 500 metres either side of the canal.

As the first phase of the project gained funding, it created positive feedback. For example, building carried out in the first phase was one of the explicit reasons the Green Infrastructure Fund decided to fund work at Queen's Cross Housing Association development.

The biodiversity benefits arising from the project attracted further funding beyond the project area, with the Scottish Biodiversity Challenge Fund installing vegetation rafts.

Regenerating brownfield sites near the city centre decreases the pressure on more natural areas at the outside of the city.

Challenges

Such a large and complex project inevitably presents challenges:

- The reporting requirements for the different funds were on different reporting cycles and had varied levels of detail required.
- The timescales of public funds were different.
- The European funding could not be matched against private investment that would result in a profit to private firms, so additional non-private investment was needed.
- The Covid-19 pandemic restrictions halted construction for some months in 2020 and added unexpected security and heavy-plant hire costs. The social distancing regulations also increased costs.

Image © Martin Faulkner

Reference for further information: [42]

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APPENDICES

APPENDIX 1: TABLE OF CHAPTER SUMMARIES AND RECOMMENDATIONS

SECTION 1: HABITAT SPECIFIC NATURE-BASED SOLUTIONS: A REVIEW OF THE AVAILABLE EVIDENCE.

Chapter 1: Woodlands	1. The UK's forests currently store around 1.09 billion tonnes of carbon and sequester about 4.6% of the country's total emissions. The UK government's commitment to plant over 30,000 extra hectares of woodland per year by 2025 offers significant opportunities to mitigate climate change through carbon sequestration, although the full benefits will not be felt before 2050. Depending on the choice of site, species and establishment method, these new woodlands could also benefit biodiversity and deliver multiple ecosystem services.
	2. Large-scale afforestation should avoid peatlands, productive agricultural lands and habitats of high conservation value, focussing instead on poor-quality grazing land of which there is more than enough to fulfil government planting commitments. However, this loss of grasslands would reduce the UK's capacity to produce meat and dairy products unless other regions were further intensified. This could do more harm than good, unless we switch to more vegetable-based diets, if tropical forests were destroyed to create pastures which supply the UK with imported meat.
	3. Small-scale establishment of native woodlands within agricultural landscapes would provide opportunities to reconnect fragments of ancient woodland, protect wildlife, and better connect people with nature if made accessible. Natural establishment of woodlands should be encouraged, where appropriate.
	4. Non-native conifer plantations provide timber and other wood products, reducing the UK's international environmental footprint. Conifer plantations can be damaging for nature, but careful planning can reduce that impact and even benefit some species. In order for plantations to meet their potential, adaptation of woodlands and forestry to future hazards is essential. This includes ensuring diversity is increased in plantations, pests and diseases are controlled, and creating complex canopy structure.
	5. Selective harvesting of trees in "neglected" native woodlands provides a source of fuelwood (i.e. a renewable energy that substitutes for fossil fuels) and other wood products. Some species thrive in selectively-logged woodlands, but felling large, old trees and clearing deadwood is harmful to birds, bats, lichens, invertebrates and fungi that are woodland specialists, so these should be avoided. They are also important carbon stores. The UK would require damaging levels of wood extraction to meet its energy demands through home-grown fuelwood.
	6. Past grant schemes aiming to support woodland creation have rarely met annual planting targets due to social factors including bureaucracy, traditional perceptions of land management, and financial viability. Local, and regional participatory approaches are needed to negotiate around different objectives and build collective power for brokering public payments for nature-based solutions (NbS).
Chapter 2: Heathlands	1. Heathlands are successional habitats that store high levels of carbon, mainly in the soil. Most types of heathlands require regular management to maintain their structure, function and characteristic assemblage of species which can conflict with climate mitigation initiatives (e.g. planting trees or allowing natural succession).
	2. Soil disturbance as a result of management actions can increase carbon emissions from the soil stock, thus soil conservation and minimal disturbance is the best mitigation tool against carbon emissions from heathland ecosystems.

	3. Heathlands undergoing shrub or tree encroachment may release carbon into the atmosphere from the soil, which will not be offset by the growing shrubs or trees for decades.
	4. Removing conifers from afforested heathland may result in some carbon emissions but will benefit the soil carbon stores and heathland biodiversity in the long term.
	5. Creating heathland from ex-arable land will result in increased carbon sequestration in soils and vegetation.
	6. Some grazing can have a positive effect on habitat quality, but it can increase greenhouse gas (GHG) emissions depending on the species and breeds. In the uplands a reduction in grazing levels on heathlands and more careful targeting of habitats suitable for burning would result in increased carbon sequestration.
	7. Restoring degraded heathland (e.g. overgrazed and transformed into grassland), will result in increased carbon sequestration in soils and vegetation.
	8. Any active climate mitigation initiatives within heathlands need to consider the resulting changes in biodiversity, including losses of heathland specialists and other open ground species.
Chapter 3: Peatlands	1. Peatlands are the most carbon-dense terrestrial systems globally.
	2. Peatlands are home to rare species and support a highly distinctive biodiversity. Many birds, mammals, invertebrates and plants found in them are specialised to some degree, and therefore dependent on the existence of these habitats.
	3. The United Kingdom's peatlands contain around 3,000 million tonnes of carbon. However, much of the UK's 2.6 million hectares of peatland is no longer actively sequestering carbon and estimates suggest that UK peatlands could be emitting 23 million tonnes of carbon dioxide equivalent (CO2e) annually.
	4. It is possible to return a proportion of these degraded areas to peat-accumulating habitats, through restoration processes, which involves rewetting and revegetation. Improvement of peatlands in this way is a permitted practice for reducing GHG emissions in any national GHG accounting systems agreed by the International Panel on Climate Change.
	5. Restoration and revegetation can slow the flow of water during some storm events and regulate catchment water flows during dry periods. Peatlands can also act as a NbS for improved drinking water quality.
	6. Trade-offs need negotiating between current land-uses and re-establishing and maintaining peatland ecosystems.
Chapter 4: Grasslands	1. Over 40% of land cover in the UK is grassland. Currently, only 2% of the UK's grassland comprises biodiverse carbon rich semi-natural grassland. Protecting this grassland is of high importance for biodiversity and avoided emissions.
	2. Acid grasslands, predominantly found in the uplands, contain around 30% more soil carbon per unit area than other grassland types. Neutral (semi-improved) grasslands, richer in species than improved grasslands, also contain marginally more soil carbon in the top 15cm of soil. Maintaining and improving species diversity in neutral grassland is critical for mitigating GHG emissions and increasing wider biodiversity.

	3. Restoring permanent grassland via reversion from improved grassland or arable land, including the restoration of wet or chalk grasslands as part of a varied (mosaic style) landscapes, can significantly positively impact biodiversity and reduce GHG emissions.
	4. Figures from the UK Land Use, Land Use Change and Forestry GHG inventory indicate that conversion of arable land to grassland has the potential for removing 8.72 million tonnes of CO2 per hectare per year (t.CO2/ha/yr) across the UK. In contrast, conversion of grassland to arable land can result in net emissions of 14.29 million t.CO2/ha/yr.
	5. Further research is needed to identify optimal sward composition and structure and associated grazing practices for GHG mitigation and enhanced grassland biodiversity which fit with production needs on intensively managed grassland. Continuous set stocking, may result in reduced carbon sequestration and biodiversity and associated impacts on ecosystem services, including water-holding capacity.
	6. Some types of grassland may be suitable for carefully selected tree planting with native species, e.g. for agroforestry or wood pasture. Agroforestry has the potential to mitigate climate change through increased carbon sequestration in vegetation and soils, storing up to 63 tonnes of carbon per hectare (t.C/yr) in temperate regions. However, a good understanding of site characteristics including vegetation communities, soil carbon at depth and hydrology is essential to avoid perverse outcomes.
	7. As well as decreasing animal numbers overall, grazing by a diverse range of animals (e.g. sheep, cattle, horse, goats, alpaca) on the same pastures can also have positive effects on grassland sward diversity and resultant GHG emissions. Shifts in grazing patterns, for example the adoption of rotational or mixed grazing, can also reduce emissions compared to continuous grazing.
Chapter 5: Arable Systems	1. Arable land is under very active management and therefore offers many opportunities to introduce NbS that enhance natural capital. The UK is at a pivotal moment in the future design of our agricultural systems as new agricultural policies will have to be designed outside the EU Common Agricultural Policy.
	2. Hedgerows are already a very important nature-based solution in arable landscapes with current estimated stocks of up to 100 t.C/ha in established hedge networks. Planting of hedges and hedgerow trees along with rejuvenation of hedges through placing them back in management cycles and are a low trade-off options for addressing climate change and enhancing biodiversity in arable systems.
	3. Field margins taken out of production benefit wildlife, leading to increased numbers of many wild species, including those that deliver important ecosystem services such as pollination and pest regulation. Soil carbon is 37% higher in soil beneath a grass margin than beneath an annual crop. Field margins can also prevent erosion and water pollution.
	4. Conservation biological control, or natural pest regulation, has the potential to reduce the need for pesticide use which could help reduce the approximate 8,300 tonnes CO2e involved in the manufacturing of pesticides.
	5. Agroforestry has the potential to mitigate climate change through increased carbon sequestration in vegetation and soils (up to 63 t.C/ha in temperate regions). It can also improve the climate change resilience of arable landscapes whilst increasing biodiversity and wider landscape diversity.

	6. Further research is required to fully understand the extent of benefits for climate mitigation and biodiversity of conservation biological control, cover crops and intercropping.
Chapter 6: Freshwater Systems	1. Freshwater ecosystems hold high biodiversity. They will be particularly affected by climate change, with changing rainfall patterns increasing the risk of flooding and drought, and rising water temperatures impacting biodiversity. Along with improved water resource management, creating habitat resilience to climate change is a high priority and requires a "wholescape" approach of linked natural environmental and socio-economic systems from uplands to the sea.
	2. Freshwater habitats play a critical role in the carbon cycle through high rates of respiration and sequestration. This is a complex area that requires further research to determine how the mitigation potential can be optimised through NbS. With the correct management, ponds are demonstrated effective carbon sinks, and should be an investment priority as they can be easily implemented across a wide scale in the UK.
	3. Planting trees to shade and cool rivers can help to protect biodiversity, and the extension of riparian forests into headwater streams can create thermal refuges and moderate temperature changes.
	4. NbS can be combined in a catchment-wide approach to manage flood risk, including tree planting, installation of log structures, creation of temporary storage ponds, removal of flood embankments and re-meandering. The current evidence base indicates solutions are effective, however most research has focused on small catchments and relied on modelling for upscaling. There is a need for consistent, large-scale empirical research in this area.
	5. Cost-benefit analyses of the use of NbS to reduce flood risk have shown potential for high net positive returns. Many of these result from complementary ecosystem services rather than avoided costs of flood damage alone. Therefore, project appraisals should consider the multiple ecosystem services provided by NbS.
	6. Changing floodplain connectivity results in potentially conflicting impacts, with some ecosystem services being synergistic whilst others conflict, and tree planting at scale may result in displacing other land uses and disturbing existing carbon stocks.
Chapter 7: Coastal and Marine Systems	1. Marine and coastal ecosystems can contain and absorb significant amounts of carbon, especially given the large area some habitats occupy. There is significant restoration potential for habitats such as seagrass and saltmarsh, given the historic loss of these habitats through pollution and development.
	2. Saltmarsh and seagrass are important carbon sinks which can be managed or restored through NbS as part of a national carbon budget. Continental shelf sediments, while having lower sequestration rates, show great potential for carbon sequestration due to covering a large area, but more uncertainties exist in the data. Kelp and other seaweeds are likely to have a role in carbon sequestration, however research into this role is still in its infancy. ▪ Saltmarsh: typical UK sequestration rate of 4.40–5.50 t.CO2/ha/yr ▪ Seagrass: average sequestration rate of 5.06 ± 1.39 t.CO2/ha/yr (specific UK figures not available) ▪ Continental shelf sediments: sequestration rate of 0.06 t.CO2/ha/yr ▪ Kelp and other seaweeds: initial estimated sequestration rate of 1.47 t.CO2/ha/yr

	3. Sequestration rates are calculated differently for marine habitats compared to terrestrial habitats, so direct comparison to terrestrial NbS in terms of climate change mitigation is difficult.
	4. Marine fauna and flora play a large role in ocean carbon cycles and will influence the carbon flux in and out of oceans. Quantifying the direct role of fauna, and indirectly of fisheries, on carbon cycles is uncertain but is an area for further research.
	5. As well as providing climate change mitigation services, coastal ecosystems provide protection from storm waves and alleviate coastal flooding. The potential for saltmarsh creation when addressing coastal defence issues is high. Coastal ecosystems also have high biodiversity, contribute to ecosystem services, especially as nursery grounds for fish, and provide human wellbeing benefits. Therefore, investment in NbS that restore or protect coastal environment is an effective mechanism of achieving a range of co-benefits with few trade-offs.
	6. Protecting and enhancing NbS in marine and coastal habitats requires consideration of fisheries regulations, particularly gear types which disturb the substrate, as well as effective management of marine protected areas for vulnerable habitats and dedicated restoration of habitats (saltmarsh and seagrass especially).
Chapter 8: Built Environment	1. The novelty of NbS for cities lies in a focus on the cost-effective provision of multiple co-benefits for many urban residents.
	2. A participatory placemaking approach to equitable co-design, co-creation and co-management of NbS that include multiple stakeholders and beneficiaries has the potential to maintain or improve biodiversity while simultaneously addressing societal issues such as climate change and other socio-environmental inequalities across both spatial and temporal scales.
	3. NbS harnesses blue and green infrastructure, such as sustainable drainage systems, green roofs, rivers, urban trees and community green spaces, which support significantly higher levels of biodiversity than constructed ‘grey’ infrastructure. These features can also help urban areas adapt to increased and more extreme temperature and rainfall events associated with climate change whilst delivering important environmental, social and economic benefits.
	4. Due to the multidisciplinary nature of NbS, its implementation in cities is inherently complex and at odds with many siloed governance structures. This is largely due to knowledge and skills gaps and the lack of coordination across sectors or departments, particularly at local authority level.

SECTION 2: EFFECTIVE IMPLEMENTATION AND DELIVERY OF NATURE-BASED SOLUTIONS.

Chapter 9: Embedding Nature-based Solutions in Strategic Spatial Planning	1. Spatial planning can used to inform decisions about delivering the right NbS in the right places. Strategic planning approaches are beginning to be integrated into wider policy and decision making in several regions. Actions can be taken by policymakers to ensure such processes become mainstream.
	2. Stakeholder partnerships should be supported to create strategic and coherent plans. Stakeholder participation, collaborative action and the community voice are vital in planning NbS to equitably meet multiple needs. Financial and technical support needs to be provided for Local Nature Partnerships and similar groups (e.g. Catchment Management Partnerships, Farmer Clusters and Neighbourhood Plans) so that they can help deliver a diverse mix of well-planned NbS that optimise synergies and manage trade-offs at landscape scales.
	3. An evidence base should be developed and maintained to inform a strategic spatial planning approach to NbS. This requires technical capacity within relevant teams (i.e. local and regional government), access tools for spatial analysis, and freely available spatial natural capital data, including both national level datasets and local data on habitat type, condition and management.
	4. Currently, many key datasets are not freely available (particularly to those outside the public sector), so natural capital maps developed by researchers cannot be shared with all stakeholders. It is important that government continues to develop free access to data, including via support for Ordnance Survey. Key to local data availability is developing a mechanism to fund Local Environmental Records Centres, so that they can continue to manage the volunteers who collect local data, and to enable them to make the habitat and species monitoring data collected freely available where appropriate. Support for the development of citizen science software applications will also play a role here.
	5. Investment is required in approaches and tools for analysing landscape level trade-offs and prioritising NbS. There is a need to support, develop and test approaches for designing NbS at landscape scale, taking into account trade-offs between different benefits. While approaches are emerging, there is a need to ensure these can assess the benefits and trade-offs for a range of intervention types.
	6. NbS should be integrated into planning and wider policies across local and national government bodies and other key organisations.
	7. Spatial planning which protects existing habitat networks and other high value natural capital assets should be embedded in the planning system. It takes many decades to reach peak values for delivering services to people.
Chapter 10: Delivering Nature-based Solutions	1. NbS should be 'mainstreamed' and integrated across all relevant policies. As a relatively new multi-sector approach with both biodiversity and societal objectives, NbS require greater profile and traction in all the policy areas they can benefit.
	2. A comprehensive and fit for purpose assessment framework is required that enables transparent assessments at multiple spatial scales and can be utilised by all key stakeholders. It needs to be able to account for the multiple benefits of the NbS initiative for both nature and climate over time, in line with defined objectives, standards, criteria and metrics.
	3. Methods to share knowledge (including local knowledge) and advice need to be built into the fabric of NbS initiatives. This is especially important when NbS are innovative practices that require new skills. Meaningful collaboration will be key to NbS and a coordinator may be instrumental in this for larger projects.

	4. The multi-stakeholder governance framework needs to incorporate carefully designed monitoring systems, with a strong foundation of baseline data, in order to determine if the ambitions of the project are being met. This will require the inclusion of biodiversity and carbon, as well as human wellbeing metrics.
	5. There is a need for continued refinement to carbon accounting and standards. More research and data gathering are necessary to improve carbon monitoring, in order to increase reliability and decrease costs. It is also important to ensure an independent examination of carbon accounting.
	6. Long-term financial support will be required for NbS initiatives and the bodies which deliver them. It will also be important to ensure that research relevant to the design, implementation and monitoring of NbS is adequately funded.
	7. Commitment to NbS research is required from UK governments to fund the necessary cross-disciplinary and cross-institution research centres for applied research that will be key for NbS innovation and evaluation.
Chapter 11: Economic Valuation and Investment Options for Implementing Nature-based Solutions	1. NbS provide multiple benefits related to climate mitigation and adaptation, biodiversity conservation and enhancement and wellbeing. Some of these ecosystem services can be valued monetarily to inform decision making, while others can be assessed in quantitative and qualitative terms.
	2. Because of the complexities of valuing all the ecosystem service flows and benefits over time and space, qualitative approaches to recognise value where it cannot be quantified can help inform decisions. Currently valuation of NbS is partial which may lead to undervaluation.
	3. NbS are effective mechanisms to create jobs and contribute to green recovery following the economic crisis caused by the Covid-19 pandemic.
	4. Governments are, and will remain, key financial investors in natural assets and their sustainable use, given the societal benefits of such investments.
	5. However, the private sector can play an important role in complementing public investments in NbS. For private finance to occur, NbS must be of appropriate scale and provide sufficient return on private investment. ▪ Lack of evidence of financial return is a major barrier to private investors. For this reason, it is important to create and disseminate information on the profitability of NbS for private investors. ▪ Innovative funding mechanisms can be used to encourage private investment, including payments for ecosystem services, catchment markets, habitat banks, regional aggregation brokers and debt instruments. ▪ Changes to regulation also have the potential to encourage private investment in NbS, for example, by requiring consideration of the use of NbS for flood mitigation, biodiversity no net-loss / net gain regulations, or make green roofs compulsory in new buildings. ▪ The role of private investment in terms of environmental outcomes and cost-effectiveness should be monitored and evaluated.
	6. The revenues generated from fiscal instruments like taxes, fees and charges can be used to finance NbS, thereby representing an additional financial source.

APPENDIX 2: RESEARCH GAPS IDENTIFIED IN THE REPORT

CROSS-CUTTING RESEARCH GAPS

Cross-cutting; carbon accounting	There is a need to standardise carbon sequestration estimates across different habitats, to ensure measurements are compatible. For example, woodland sequestration rates are calculated using biomass estimates as a large percentage of the final value. Aquatic habitats tend to focus more on carbon buried in sediments. Without this standardisation, any attempt at carbon accounting across different habitats could be flawed. Further research into refining carbon accounting and monitoring is required to allow for effective habitat comparisons to be made.

SECTION 1: HABITAT SPECIFIC NATURE-BASED SOLUTIONS: A REVIEW OF THE AVAILABLE EVIDENCE

CHAPTER 1: WOODLANDS

Woodlands; timber production; climate change mitigation	Calculating the abatement potential of managed woodlands requires complex carbon accounting that transcends industrial sectors and tracks the persistence of harvested products through time. Further research to create a more robust evidence base is required as these accounts are currently rarely available.
Woodlands; climate change mitigation; carbon sequestration	The mitigation potential of UK forests is affected by three poorly quantified phenomena. First, conifer plantations absorb more solar radiation than deciduous broadleaf forests, and thereby warm the atmosphere. The large-scale transformation of Europe's broadleaved forests to conifer plantations over the past three centuries has contributed to global warming, largely counteracting the climate benefits of locking additional carbon in forest biomass and soils. Secondly, tree planting can reduce soil carbon stocks. About 70% of forest carbon is held in the soil, and site preparation typically releases carbon from stores, creating an initial "carbon debt" which needs to be repaid before management delivers any climate benefit. Trees also alter the quality of soil organic matter as they grow with long-term consequences for carbon storage. Thirdly, the removal of carbon from forest ecosystems via stream-water transport , is poorly quantified. Further research into these factors is required to refine predictions of carbon drawdown associated with woodland establishment and management.

CHAPTER 2: HEATHLANDS

Heathlands; climate change mitigation potential	The main studies looking at soil carbon content in the UK group together "moor and heath". As a result, it is currently difficult to extrapolate the impact of management on the carbon stores of particular soils. Further studies comparing mineral and organic soils, across a range of geographical locations, in the uplands and lowlands, would fill a significant evidence gap.

Heathlands; carbon fluxes	There has been some research in the last two decades on the impact of management on the carbon fluxes of dwarf shrub heath habitats. However, the information available is still limited. Studies show a large range of results, a reflection of the heterogeneity of the habitat as a result of climate, geography, history, management and conservation status. Further research into carbon fluxes in dwarf shrub heath habitats is required.
Heathlands; management	Although the impact of management interventions in terms of carbon emissions or sequestration can be used to assess the likely impact, it is currently difficult to apply directly to specific sites. Further studies are needed that cover the range of the geographical distribution of heathlands in relation to effects of management interventions. In particular more experimental studies looking at vegetation on different soil types.

CHAPTER 3: PEATLANDS

Peatlands; natural flood management potential	Alongside acting as a major UK carbon store, peatlands can act as NbS to help adapt to a changing climate by acting as Natural Flood Management (NFM) systems. It is clear that restoring (including the blocking of drainage ditches) and revegetating (through the re-introduction of Sphagnum moss) can slow the flow of water during some storm events. More research needs to be conducted to evaluate the full potential of peatlands across different catchments.
Peatlands; peatland burning	Factors such as burn intensity, frequency, area covered, vegetation structure, time of year, and the degradation status of the peatland all play a part in the resulting changes to biodiversity and carbon sequestering ability of the peat following a burning programme. Further studies are required that take into account these aspects, need to be conducted to further understand the impacts of fire on a range of peatland habitats.

CHAPTER 4: GRASSLANDS

Grasslands; management; carbon storage	There is currently a lack of understanding about the processes leading to carbon storage at depth (below 15cm), its relationship with biodiversity above and below ground and how it is affected by field management practices needs to be addressed. Further research is required to gain a better understanding of these processes and how they relate to food production (both quantity and quality). Preferably this research would be developed alongside farmers as this will help to determine appropriate land management practices in relation to mitigating or reversing biodiversity loss and climate change impacts.
Grasslands; tree planting	Further research is required on approaches to planting trees on or around grassland for maximising grassland and biodiversity, whilst enhancing or minimising agricultural outputs, is already available. However, to mainstream these and other practices it is likely to be important to work with land managers to gather further evidence across a range of approaches and locations and to understand how to encourage/motivate farmers to take up novel practices.

Grasslands; national parks, AONBs	In areas of particular cultural interest (e.g. for tourism, recreation, inspiration etc.) such as the National Parks and AONB's, there is a particular challenge around how to enhance biodiversity and carbon storage whilst continuing to maintain/enhance these cultural ecosystem services which result in vital income for many of these areas, e.g. maintaining profitable livestock enterprises. Further research is required on how to enhance biodiversity and carbon storage whilst continuing to maintain and enhance the cultural benefit they provide.
Grasslands; sward composition	Continuous set stocking, may result in reduced carbon sequestration and biodiversity and associated impacts on ecosystem services, including water-holding capacity. Further research is needed to identify optimal sward composition and structure and associated grazing practices for GHG mitigation and enhanced grassland biodiversity which fit with production needs on intensively managed grassland.

CHAPTER 5: ARABLE SYSTEMS

Arable; general	There is a range of research on the economic costs and benefits of restoring degraded agricultural land, the results are varied and generalisable information that can be scaled up is not readily available. Further research on the economic costs and benefits of restoring degraded agricultural land is required.
Arable; general	Some studies on biodiversity decline in relation to agriculture indicate a more complex picture than a steady decline in biomass. Further investigation and research is needed in this area.
Arable; herbaceous field margins	The balance of the soil community is also important with regards to the climate mitigation potential of field margins, as soil biota are both involved with decomposition processes and the release of GHGs as well as formation of soil organic matter and carbon sequestration. The overall impact of biota on GHG cannot yet be quantified. Further research is needed to establish the overall impact of biodata on GHG emissions and sequestration to assess their effectiveness to act as a NbS for climate change mitigation.
Arable; conservation biological control	Potential benefits of conservation biological control can include yield gains and a reduced requirement for pesticides, indirectly reducing the GHG emissions associated with pesticide manufacturing (approximately 8,300 tonnes CO_2e) which are about 9% of the total associated with UK arable crop production . However, these benefits are not found in every circumstance. Further research into conservation biological control is required.
Arable; intercropping	The data available for intercropping is more equivocal and less certain. For intercrops, the limited studies available show mixed results regarding GHGs. Whilst the majority of information on cover crops comes from annual cash crops, information on intercropping derives from both agroforestry systems and from annual cash crops. There is some evidence that the value of intercropping comes from improved nitrogen use efficiency, especially when legumes and non-legumes are mixed , and the potential for reduced fertiliser inputs if legumes are used. More evidence is required across globally distributed sites to draw clear conclusions.
Arable; cover cropping	There is more variation on the effect of cover crops on the direct emission of greenhouse gases, especially carbon dioxide (CO_2) and nitrous oxide (N_2O). Further research is needed to increase understanding.

Arable; trade-offs; agroforestry	More simple models are needed to elucidate the productivity of agroforestry systems. Further research to assess the productivity and create these models is required.
Arable; conclusion	Interventions can involve a reduction of arable activity and such trade-offs must be considered. Further research into the application of NbS in agricultural landscapes is required in order to establish both the direct and indirect impacts, positive and negative, of such interventions.

CHAPTER 6: FRESHWATER SYSTEMS

Freshwater; climate mitigation	The mitigation potential of freshwater habitats is a complex area. Despite covering less than 4% of the earth's surface, evidence suggests that freshwater systems play an important role in the carbon cycle. Whilst the limited data available indicates large mitigation potential, there is uncertainty. Further research is required to understand the full effects and how these can be optimised through the use of NbS.
Freshwater; ponds; carbon burial; carbon storage	Limited UK evidence indicates that the carbon burial and storage potential of ponds is promising when appropriate management practices are applied. One study reports an average carbon burial rate in typical lowland UK ponds (over 18-20 years) of 5.21 tonnes of carbon dioxide per hectare per year (t.CO2/ha/yr) (range 2.90–9.06) once the pond is over 2-3 years old and vegetated , but it is unclear how long such rates may be sustained, particularly at the landscape scale with shallow ponds subject to a range of pressures. Further research indicating the carbon burial and storage potential of ponds is required. Research indicating how long such burial rates are sustained is also required.
Freshwater; ponds; carbon storage	Recent evidence shows UK pond sediments store relatively high levels of organic carbon, for example a block of sediment one ha in area and 10 centimetre (cm) deep holds between 30 and 60 tonnes of carbon (t.C). Diverse vegetation appears to be the main factor driving higher storage, whilst surrounding land use is less important, suggesting that ponds could be effective across many different landscapes. There is limited evidence that the precise plant mix may be important, with common pond plants such as species of *Ranunculus* and *Sparganium* found to be beneficial. Further research into pond vegetation in this context is required.
Freshwater; ponds	It is important to understand the lifespan of ponds, which is potentially limited by changing agricultural practices and natural infilling, and the impact this may have on their long-term potential as NbS. Further research into the life cycle of ponds and how this might impact their long term potential as NbS is required.
Freshwater; rivers; streams	Inland rivers and streams play a significant role in the carbon cycle through moving carbon from the land to the ocean, where it can be absorbed, buried in sediments or released back into the atmosphere (see Chapter 7). However, rivers and streams are also a source of carbon . Further research into how this part of the carbon cycle can be optimised through NbS is required.

Freshwater; lakes	Enhanced carbon burial by lakes may be a positive side-effect of the otherwise negative impacts of eutrophication, which include increased water treatment costs, biodiversity loss, ecological change and loss of amenity value lakes. However, eutrophication also results in increased emissions of other greenhouse gases (e.g. methane). Further research is required to determine whether restoration of lakes to clear water would result in them being a source or sink overall, as well as the impact on other ecosystem services of lakes.
Freshwater; lakes	In lakes, increasing depth has a negative impact on the sequestration potential. Further research is required to determine why this happens.
Freshwater; lakes; carbon fluxes	Evidence suggests lake sediments may switch between being a carbon source and sink and, given the significance and scale of these fluxes, understanding this is essential to assessing the ultimate net effect of carbon processing and how this can be optimised through management. Further research is required as evidence is currently limited.
Freshwater; flood management	NbS can be combined in a catchment-wide approach to manage flood risk, including tree planting, installation of log structures, creation of temporary storage ponds, removal of flood embankments and re-meandering. The current evidence base indicates solutions are effective, however most research has focused on small catchments and relied on modelling for upscaling. There is a need for further research which is consistent, large-scale and empirical.
Freshwater; tree planting	Widespread woodland creation (by planting or natural colonisation) in the uplands and headwater gathering grounds can help to reduce runoff generation, though direct evidence shows an uncertain overall impact on flood flows. Further research us required to assess the impact of tree planting on flood flows.
Freshwater; flooding	Runoff attenuation features 'slow and filter' surface water runoff in the landscape; for example, placing engineered log structures in headwater stream channels has been shown to potentially decrease flooding downstream . Empirical results from the Eddleston study show the impact of in-stream log structures and temporary storage ponds in delaying the rise in peak flood waters for a catchment of at least 25 km. Along with the creation of soil, wood or stone barriers across flow paths, and the removal of river embankments to enable water to spill onto the floodplain, these NbS can be effective for small one in two year events in small catchments. However, there remain issues of how realistic modelling approaches are for upscaling this and there is currently limited empirical evidence to support this for greater flood events or across larger catchments. Further research is required in relation to greater flood events or event that happen across larger catchments.
Freshwater; lakes	Long-term studies on lake systems have shown significant temperature increases particularly in areas of shallow water during the summer, when flows are low. Whilst further work is required to assess the impact of catchment land use change (e.g. afforestation) on standing waters and this mostly applies to shallow, smaller waters, it is clear that creating and maintaining thermal refuges by, for example selectively increasing depth and introducing shading is an important response to temperature changes. Further research is required to assess the impact of catchment land use change on standing waters.
Freshwater; climate change	The effectiveness of NbS at addressing climate change and providing biodiversity benefits is variable between measures and across scale. Further research and evaluation is needed in this area.

Marine; kelp; carbon sequestration	Kelp and other seaweeds are likely to have a role in carbon sequestration, however research into this role is still in its infancy. Further research into the role kelp and seaweed have for carbon sequestration is required.
Marine; fauna	Quantifying the direct role of fauna, and indirectly of fisheries, on carbon cycles is uncertain. Further research to quantify the role of fauna and fisheries on the carbon cycle is required.
Marine; carbon storage	A global study of carbon storage in seagrass sediments over the first one metre of depth finds carbon stocks to vary from 23 to 352 tonnes of carbon per hectare (t.C/ha), with values from the UK falling approximately within the ranges 98 to 380 t.C/ha. The sequestration rate of this carbon also varies, but data and understanding are much more limited. Further research into the carbon storage of seagrass sediments is required.
Marine; carbon storage; carbon sequestration	Significant evidence gaps remain in understanding the full CO_2 storage and sequestration services provided by continental shelf carbon sink habitats, especially sedimentation rates and release through seabed disturbance such as trawling. More research is required to improve their role in contributing to carbon sequestration
Marine; kelp	The cost of restoring kelp habitat is largely unknown. Further research is required.
Marine; kelp	Kelp is highly productive and has a rapid growth rate. Most kelp growth is eaten by grazers, and ultimately turned back into CO_2 through respiration. However, new evidence suggests that around 5% of kelp could be sequestered and stored in marine sediments. Based on productivity figures for Scottish kelp beds, this could equate to 1.47 t.CO2/ha/yr in UK waters. However, there is great uncertainty in this estimate. Further research into the productivity of kelp beds is required.
Marine; climate mitigation; macro algae	Data for kelp are more developed than for other macroalgae communities including intertidal algae. Kelp also shows faster growth than many other algal species. It is likely that other macroalgae contribute further to these figures, but as indicated above, there is already considerable uncertainty in the data. Research into the fate of macroalgal carbon is an important area for future research, and marine algae has potential to be considered as a NbS.
Marine; fauna; climate mitigation	There is a potential that recovery of fish and marine mammal stocks (ideally well above maximum sustainable yield values) will have potentially large net benefits to carbon sequestration in coastal and open waters. The evidence is currently relatively sparse, and the magnitude of the effect is uncertain. Further research into this area is required.
Marine; general	There is considerable uncertainty in the role of many habitat types, including biogenic reefs and molluscan shellfish formation as a carbon source or sink. Further research into this area is required.
Marine; emissions	Recent research has also investigated production of methane and nitrogen oxides by coastal habitats. The research is still developing and does not provide a clear picture for the UK, however, methane production by coastal ecosystems is likely to occur at low rates but could be important given that methane has a 25 times higher global warming potential than CO_2. Further research is required into the production of methane by costal habitats.

Built environment; urban; blue and green infrastructure	There are still knowledge gaps regarding species selection for blue and green infrastructure and the optimum design of greenspaces for cooling. Further research into this area is required.
Built environment; economy	In general, neither short long-term economic benefits of NbS have been fully quantified. Further research into the long term and short term economic benefits of NbS is required.
Built environment; challenges	Improved long-term monitoring and evaluation are needed to produce stronger evidence that captures the broad values and benefits associated with NbS, including how impacts differ across different social groups. Further research into long-term monitoring of NbS is required.

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