Nature-based solutions as climate change adaptation measures for rail infrastructure

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Abstract

Globally, railways provide vital social and economic functions by enabling the movement of people and cargo across cities, countries and continents. Rail infrastructure is therefore critical to the ongoing delivery of safe and efficient passenger and freight train services. However, railway assets are extremely vulnerable to extreme weather events such as temperature extremes, droughts, floods and storm surges. The projected escalation in the intensity and frequency of extreme weather conditions due to climate change is likely to increase the damage to and inoperability of rail infrastructure. This presents a significant challenge to the rail industry worldwide, as the failure to proactively adapt its infrastructure to withstand the impacts of a changing climate will significantly increase service disruption and potentially compromise the safe operation of rail networks. To date, climate change adaptation (CCA) options for rail infrastructure have generally involved grey (engineered) interventions. This research proposes and investigates the potential suitability of applying Nature-based Solutions (NbS) as alternatives or complements to grey adaptation techniques for use in the rail context. NbS can provide ecologically sustainable means to adapt infrastructure to withstand and/or accommodate the impacts of current weather extremes and those anticipated under future climate change, whilst also delivering a range of valuable co-benefits. Very few examples of the application of NbS have been observed in the rail environment thus far.

This research used systematic literature reviews to identify instances of NbS use for CCA in rail, and in non-rail scenarios which may be applicable to the rail sector, and to investigate the potential barriers and aids to NbS deployment by the industry. An online questionnaire was then utilised to explore the knowledge, experience, and perspectives of 55 rail industry professionals with regards their perceived and/or in practice obstacles and aids to the use of NbS for CCA on rail infrastructure. This was followed by case study research performed on the application of NbS on two rail case studies in Adelaide, Australia, and Yorkshire, UK. Findings from the barriers encountered and the aids to NbS implementation on these live rail examples, combined with rail stakeholder engagement, have been used to develop a framework tool for use by the industry to operationalise NbS for CCA.

Whilst this study confirms multiple examples of NbS being used in rail which are not included in the literature, results from the mixed methods applied in this research corroborate that a lack of awareness of the NbS concept is the principal barrier to its dissemination in the industry. The provision of education on NbS to the rail sector will therefore be essential to its widespread operationalisation; the outputs of this study, including rail audience specific case studies and diagrammatic tools, contribute to rail industry knowledge to support this. Legislation, policy and standards were also highlighted as key tools to support NbS uptake by the rail industry. The use of rail demonstration sites is therefore recommended to gather robust evidence of NbS performance in the rail context to inform legal instruments, specifications and guidance, as well as providing real-life NbS awareness to rail stakeholders and neighbouring communities. These endeavours, along with the testing of the framework proposed in this study, will support the further research on and trialling of NbS concepts in the rail sector which are urged to enable the industry to implement NbS as credible CCA measures, supporting the ongoing provision of reliable, resilient rail infrastructure.

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Author's Declaration

I declare that, except where explicit reference is made to the contribution of others, that this dissertation is the result of my own work and has not been submitted for any other degree at the University of Glasgow or any other institution.

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Signature:

Chapter 1 Introduction

1.1 Context

With over 1.3 million km of railway lines worldwide (Statista, 2023), rail infrastructure represents a significant global asset (International Union of Railways, 2022; Palin et al., 2021). Human-induced climate change, triggering more frequent and more extreme weather events, has caused widespread adverse impacts to transportation infrastructure (IPCC, 2022), including railways, globally (Garmabaki et al., 2021; Palin et al., 2021). The main threats to the rail network are increasing temperatures and changes in precipitation (Chinowsky et al., 2019; DeVinne et al., 2022). To withstand the currently faced weather extremes, and those projected in a changing climate, rail organisations worldwide must seek measures to protect their infrastructure from, and adapt it to accommodate, the impacts of climate change, and ensure that this is accounted for in the ongoing planning, design and maintenance of rail infrastructure (Climate Adapt, 2019; Quinn et al., 2017). The identification of cost-effective and environmentally sustainable climate change adaptation (CCA) measures and their integration to the long-term management of rail infrastructure therefore poses a complex challenge for the industry (Chapter 2; Wang et al., 2020a). A preliminary literature search found very limited coverage of CCA in the rail industry, confirming the need for further research on this topic (see Chapter 2).

The limited data that exists on CCA interventions used in rail reveals that measures typically involve ‘grey’ engineered structures (e.g., flood defence walls), and ‘soft’ management solutions (e.g., policies and planning). This thesis introduces the concept of applying ‘Nature-based Solutions’ (NbS) as CCA measures for rail infrastructure, and provides a framework for use by the rail industry to aid their implementation.

NbS are defined by the International Union for Conservation of Nature (IUCN) as “actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits” (Cohen-Shacham et al., 2016, p. 4). An ecosystem is a “dynamic complex of plant, animal and microorganism communities and the non-living environment interacting as a functional unit" (Millennium Ecosystem Assessment, 2005, p. v). More recently, the IUCN definition has been supplemented by the United Nations (UN) Environment General Assembly which describes NbS as "actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience and biodiversity benefits" (United Nations, 2022, p. 2). The exploration of NbS as CCA measures for rail in this research, as aligned with both the IUCN and UN definitions for NbS, is outlined in Table 1-1.

The IUCN frame NbS as an "umbrella concept" that encompasses a range of ecosystem management approaches that address societal challenges (Cohen-Shacham et al., 2016, p. 10); Figure 1-1 presents the IUCN's five categories of NbS approaches and examples of each.

Table 1-1 Exploration of NbS implementation as CCA for rail infrastructure in this research aligned with IUCN and UN NbS definitions

IUCN Definition (Cohen-Shacham et al., 2016, p. 4)	**UN Definition** (United Nations, 2022, p. 2)	**How this research explores NbS implementation on rail infrastructure for CCA**
"actions to protect, sustainably manage, and restore natural or modified ecosystems,	"actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems	This research identifies practical techniques that involve the introduction, management and/or restoration of vegetation, including the complementary use of natural solutions alongside 'grey' measures as 'hybrid' options, which can be applied in the rail environment in response to climate change.
that address societal challenges effectively and adaptively,	which address social, economic and environmental challenges effectively and adaptively,	This research considers the application of NbS to address the impacts of climate change as a globally significant social, economic and environmental challenge. It recognises the social and economic value of passenger and freight rail transportation. The thesis also documents the climate change mitigating environmental benefits of rail as a green travel mode along with the carbon emission benefits of implement NbS as a less carbon intense CCA solutions than traditional grey engineered measures. It considers factors that may impact the successful, effective, implementation of NbS in the rail environment, and the impact that a changing climate may have on NbS performance, including the need for the CCA measures and vegetation selected being suitable for and/or being able to adapt to the climate to which they are exposed.
simultaneously providing human well-being and biodiversity benefits".	while simultaneously providing human well-being, ecosystem services, resilience and biodiversity benefits".	This thesis documents multiple additional social and environmental benefits that can be enabled through the use of NbS, sourced through literature review, stakeholder consultation and case study examination.

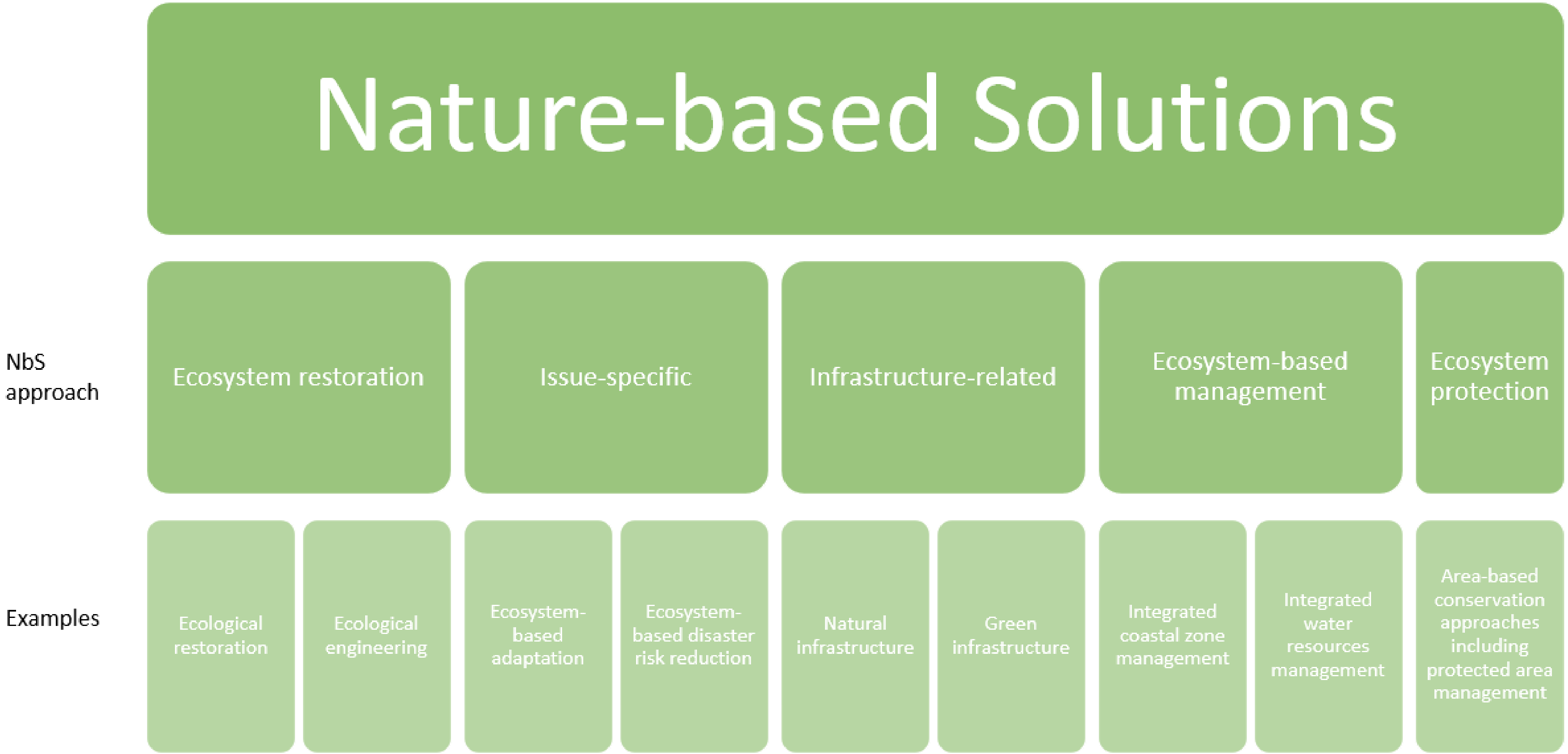

Figure 1-1 Nature-based Solutions as an umbrella concept: Categories and examples of NbS approaches
(Adapted from Cohen-Shacham et al. 2016, p.10)

As further discussed in Chapter 2, the ‘issue-specific’ and ‘infrastructure-related’ NbS approach categories - specifically Ecosystem-based adaptation (EbA), Ecosystem-based disaster risk reduction (Eco-DRR) and Green Infrastructure (GI) - are particularly relevant to CCA for rail infrastructure. The ecosystem ‘regulating services’ provided by NbS, i.e., those services that beneficially influence pressures to society including climate and floods (Millennium Ecosystem Assessment, 2005), can help to protect rail assets from, and/or adapt the infrastructure to accommodate, climate related hazards such as flooding, erosion, drought, heat and landslides (Van Zanten et al., 2023). In addition to addressing the societal challenges posed by these climatic hazards, the use of NbS can deliver a range of further benefits through the ecosystems’ (typically simultaneous) delivery of provisioning, cultural and supporting services (Millennium Ecosystem Assessment, 2005), examples of which are shown in Figure 1-2.

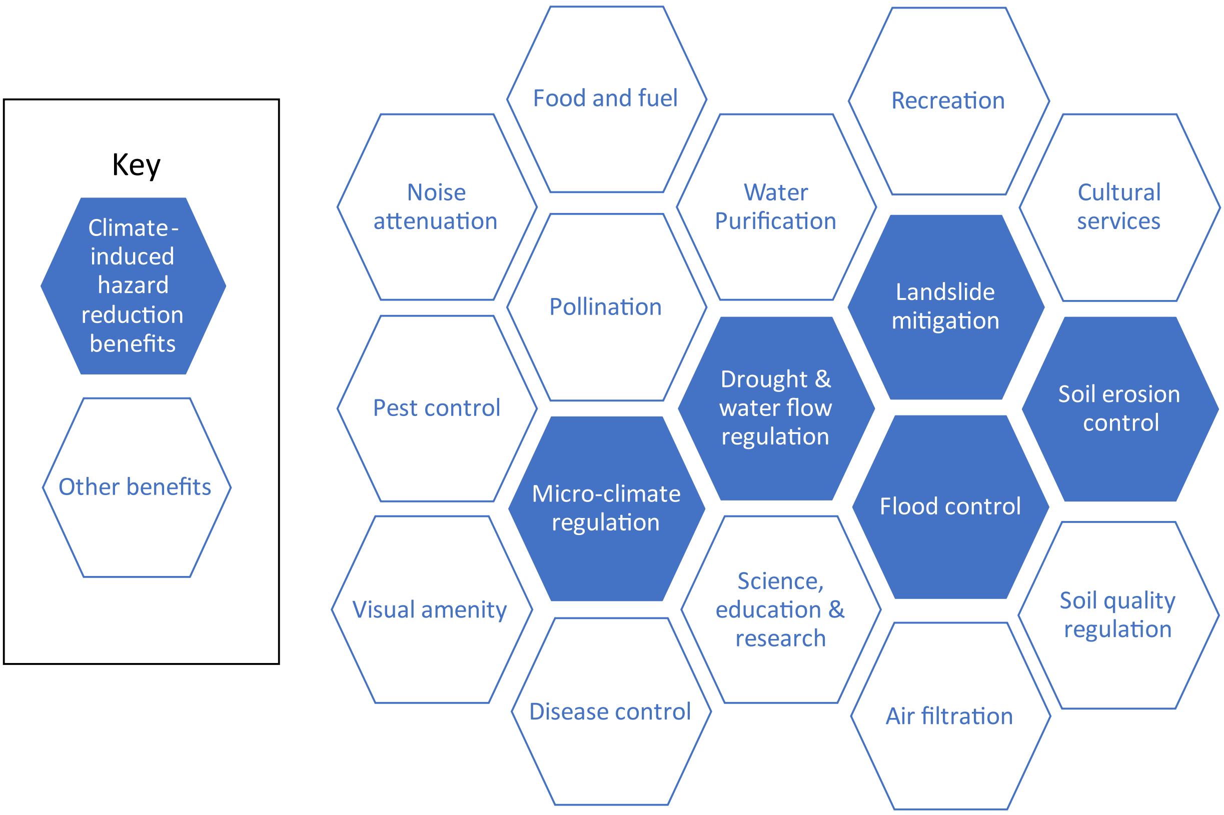

Figure 1-2 A selection of benefits from the implementation of Nature-based Solutions
(Adapted from: NCAVES and MAIA (2022))

An example of such measures are vegetated drainage systems. In an approach referred to as Sustainable Drainage Systems (‘SuDS’), vegetation can be incorporated into drainage systems to help manage rainfall and control surface water (susdrain, 2023). SuDS transport surface water and slow down runoff before it enters watercourses; they enable surface water infiltration into the ground, and evapotranspiration from the vegetation (susdrain, 2023). In addition to regulating rainfall and storm water flow, the use of SuDS can improve air and water quality, provide cooling effects, whilst delivering biodiversity and aesthetical benefits. Figure 1-3 shows vegetation adjacent to the track in Canberra, Australia, installed as part of the SuDS that have been put in place along the light rail route (Canberra Metro Operations, 2023). In addition to controlling surface water run-off which prevents flooding of the track and associated disruption to light rail services, rainwater is harvested from the track via the SuDS for the future irrigation of the vegetation (as a further sustainable design consideration, drought resistant native plant species were selected to reduce watering requirements) (Canberra Metro Operations, 2023).

Figure 1-3 Sustainable drainage system adjacent to the track on Canberra Light Rail, Australia
(Source: Blackwood, 2023)

There is growing recognition that ‘green’ NbS can be used as alternatives to, or in a hybrid manner with, ‘grey’ solutions to protect or adapt infrastructure (Seddon et al., 2020a). Several NbS concepts have been proposed as alternatives and/or complements to the CCA measures currently implemented in rail; however, very few live examples of the use of NbS on rail exist (refer Chapter 2).

With the overarching aim of assessing the potential integration of NbS as CCA measures for rail, this thesis documents the development of an operationalisation framework that has been created based upon the outcomes of systematic literature review, and refined and enhanced following the testing of its application on two live rail examples and engagement with rail industry professionals, in the UK and Australia. The body of work was framed by the following research questions:

1. What is the evidence base on the use of NbS being implemented as CCA measures in the railway context?
2. Are there NbS being used as CCA measures in rail which are not included in the literature?
3. What are the challenges and barriers to the operationalisation of NbS as CCA measures for the rail industry?
4. What could aid the operationalisation of NbS as CCA measures for the rail industry?

The empirical data in response to these questions, including iterations of the framework, are catalogued in four research papers which have been published in peer-reviewed journals, and form the main body of this thesis.

The remainder of this introduction provides an overview of climate risk to rail infrastructure, and the problem and significance of this issue. A summary of prior research relevant to this body of work is provided. This is followed by an outline of this study's research questions and objectives, and an overview of and justification for the research approaches and methods employed to address these.

1.2 Rail infrastructure and climate risk

1.2.1 Rail infrastructure

Rail infrastructure is defined as the facilities that are necessary to enable the safe operation of a railway (New South Wales Government, 2012). It comprises:

- Railway tracks (steel rails secured on sleepers), generally laid on granite (or a similar material) ballast stones, or, less commonly, a concrete 'slab track' (The Railway Technical Website, 2019);

- Signalling, communication and data management systems;
- Electrical power supply and traction systems, including overhead wiring;
- Civil engineering components including earthworks and drainage;
- Railway structures including bridges, tunnels and viaducts;
- Associated buildings, depots, yards and workshops; and,
- Supporting plant, machinery and equipment (New South Wales Government, 2012).

Rail infrastructure does not include 'rolling stock' i.e., vehicles that operate on or use a railway such as trains, locomotives, trolley and wagons (New South Wales Government, 2012).

Railway infrastructure is therefore a "complex and multidisciplinary engineering system" (The Railway Technical Website, 2019). The numerous and diverse range of rail infrastructure constituents means that there are multiple components to bear in mind when considering climate change risks to and impacts on railways (see Chapters 1.2.2 and 2.1), presenting multifaceted challenges to the rail industry when seeking system-wide CCA solutions.

1.2.2 Climate risk and rail infrastructure

Following the Intergovernmental Panel on Climate Change (IPCC) approach which applies the concept of risk to frame the understanding of climate change impacts, risk can be defined as a function of the interaction of climate hazards with exposed and vulnerable social and ecological systems (Reisinger et al., 2020). The risk introduced by human responses to climate change is a further component of risk considered by the IPCC (IPCC, 2021; Reisinger et al., 2020). Frequently used climate risk terminologies and their relevance to rail infrastructure, as applied in this thesis, are detailed in Table 1-2.

Table 1-2 Climate risk terminology as applicable to rail infrastructure

Climate risk determinant	Relevance to rail infrastructure
Risk	The potential adverse impact to the ongoing safe, reliable and cost-effective provision of rail services.
Hazard	Climatic hazards to rail infrastructure are manifested through hydro-meteorological hazards (HMH). HMH are hydrological, atmospheric and oceanographic phenomena (e.g., temperature extremes, droughts, floods and storm surges) (United Nations Office for Disaster Risk Reduction, 2021) that can cause damage to infrastructure, threaten the safe and timely provision of rail services, shorten design lives and increase operation and maintenance costs (Chapter 2).
Vulnerability	The low flexibility of rail infrastructure and services makes railways particularly susceptible to the impact of HMH (Lindgren et al., 2009; Network Rail, 2015), for example when compared to roads which can provide alternative routes (Wang et al., 2020b).
Exposure	The global reach of rail networks, which includes cross-continental routes, means that railways are subjected to HMH continuously (Quinn et al., 2017). Its common placement along coastlines means that rail infrastructure is located in settings that could be adversely impacted by HMH (Jaroszweski et al., 2010; Reisinger et al., 2020; Thornes, 1992). Rail infrastructure is typically used to connect urban settlements; siting the assets in built up environments can expose the assets to extreme climate hazards, amplifying the impact, particularly when multiple interdependent assets are simultaneously exposed to the same hazard (IPCC, 2022) e.g., rail signalling systems are dependent on electricity and telecommunication infrastructure which may be impacted by extreme weather events.

Climate risk determinant	Relevance to rail infrastructure
Adaptation	The IPCC define adaptation as “the process of adjustment to actual or expected climate and its effects in order to moderate harm or take advantage of beneficial opportunities” (IPCC, 2022, p. 43). Adjustment may entail: Retreat (i.e., avoid the effects of climate change), Protection, or Accommodation (Eichhorst, 2009), where the latter two processes may involve ‘grey’, ‘green’ or ‘hybrid’ CCA measures (Cohen-Shacham et al., 2016). Currently used grey, and proposed green, nature-based CCA options for rail infrastructure are detailed in Chapter 2.
Response	Actions taken to respond to climate change. Responses may involve adaptation (see above), and mitigation, to limit or prevent greenhouse gas emissions, for example through the decarbonisation of rail by shifting from diesel to renewably sourced fuels (International Energy Agency, 2019). Mitigation responses can also include activities to remove greenhouse gases from the atmosphere. NbS can simultaneously provide CCA and mitigation functions whilst delivering additional benefits such as the restoration of ecosystems (United Nations Environment Programme and International Union for Conservation of Nature, 2021). Maladaptation may occur if CCA actions fail to consider long-term impacts of the adaptation options (IPCC, 2022), for example, the installation of flood defence structures may significantly alter the natural adaptive capacity of flood-prone areas, making railways more vulnerable to flood hazards (Chapter 2).
Resilience	The ability of railways to “provide effective services in normal conditions, as well as to resist, absorb, accommodate and recover quickly from disruptions or disasters” (Bešinović, 2020, pp. 5-6).

1.3 Problem and significance

In their 2023 Global Risks Report, the World Economic Forum (2023) rank the failure to mitigate climate change, the failure of CCA, and 'natural' disasters and extreme weather events as the top three global risks of the next decade, yet we are the least prepared for these risks, which poses problems in terms of risk prevention or mitigation. As "human-caused climate change is already affecting many weather and climate extremes in every region across the globe" (IPCC, 2023, p. 5), and with climate change affecting "all parts of railways in all parts of the world" (Quinn et al., 2017, p. iii), the changing climate presents a rapidly increasing risk to the rail sector (International Union of Railways, 2023b).

Damage to rail infrastructure, e.g., landslips on railway embankments, and conditions that impede its use, e.g., flooding (both scenarios are caused by high precipitation events, the frequency and intensity of which have increased in many regions of the globe with climate change (IPCC, 2022)), can cause widespread disruptions to the rail network. The significant extent of such scenarios is unfortunately demonstrated by the derailment of a passenger train at Carmont in Aberdeenshire, UK in August 2020 which caused the death of three people and injury to six others onboard. The train derailed after striking debris washed onto the track following an extreme rainfall event (BBC News, 2023; Rail Accident Investigation Branch, 2022).

By connecting goods to markets and people to employment and social facilities, rail infrastructure fulfils critical societal and economic functions by enabling the provision of safe, reliable, environmentally efficient, and cost-effective rail services (Koks et al., 2019; The World Bank, 2022). Disruption to rail services gives rise to delays, and in some instances, the complete loss of services, and can therefore produce significant detrimental social and economic consequences (Ilalokhoin et al., 2022). Compromised rail mobility can lead to the interruption of freight transportation and essential supply chains, including food and medicine, for example, and people can be left unable to access employment, healthcare and other basic amenities (United Nations, 2021b). In the UK, extreme weather events account for approximately 20% of all rail network delays, equating to an average of 1.5 million train delay minutes per year (DeVinne et al., 2022). Meanwhile, it is estimated that the costs of climate-related disruption to rail services on the

United States' rail network alone could range from USD$103 to USD$138 billion by 2100 (Chinowsky et al., 2019). The need for the rail industry to manage its existing and any new infrastructure to withstand, and quickly recover from, current weather extremes, and those anticipated with a changing climate, is therefore growing urgently (Nolte (n.d.); Chapter 2; Chapter 3).

At a broader level, it is important to recognise the imperative role that rail infrastructure provides globally as a sustainable transport system through its enablement of the safe, affordable, and low-emission mobility of people and goods (United Nations, 2021b). The ongoing provision of sustainable rail infrastructure directly contributes to the United Nations' (UN) 2030 Agenda for Sustainable Development (United Nations, 2021b), and its Sustainable Development Goals (SDGs) (United Nations, 2023a). Specifically, the implementation of CCA measures, including NbS, on rail infrastructure helps the sector to fulfil SDG 9 Industry, Innovation and Infrastructure, in particular Target 9.1 to "Develop quality, reliable, sustainable and resilient infrastructure, including regional and transborder infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all" (United Nations, 2023c) (alongside Target 9.4 regarding the upgrade of such infrastructure). The use of NbS concepts, including EbA and Eco-DRR, will also support SDG 13 Climate Action Target 13.1 to "Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries" (United Nations, 2023d) through managing, restoring and conserving ecosystems to increase the resilience of people, or reduce vulnerability or risk (UNDRR, 2021), whilst also providing the multiple other benefits shown in Figure 1-2. Sustainable, resilient transport is central to the achievement of many SDGs, the UN estimating that it may indirectly support the achievement of up to 92% of all SDG targets (United Nations, 2021b). Furthermore, well-designed and managed CCA options, which may include NbS, can reduce the vulnerability of natural and human systems, and therefore also have many synergies towards achieving the SDGs (United Nations Environment Programme, 2021a). Again, this strengthens the case for investigating the suitability of NbS as CCA for rail infrastructure.

Efforts to implement NbS for CCA will also provide a means for railway organisations, collectively at a country level, to contribute to their respective national climate action plan as required under the legally binding international treaty on climate change, the Paris Agreement (2015) (United Nations, 2023g; United Nations Framework Convention on Climate Change, 2015). The Agreement establishes a global goal on adaptation through the "enhancing of adaptive capacity, strengthening resilience and reducing vulnerability to climate change" (United Nations Framework Convention on Climate Change, 2015, p. 5). It requires parties to outline their domestic carbon emission reduction and adaptation measures as Nationally Determined Contributions (NDCs) that they intend to achieve (United Nations, 2023f), and publish their adaptation plans and priorities in Adaptation Communications (United Nations, 2023b; United Nations Framework Convention on Climate Change, 2018). The sharing of NDCs and Adaptation Communications in their respective UN Framework Convention on Climate Change (UNFCCC) Registries ensures visibility of each party's endeavours, the latter communications being of particular value to this research due to their intended purposes to increase the visibility and undertaking of, and enhance awareness on, adaptation actions, including the provision of support to developing countries (United Nations Framework Convention on Climate Change, 2018). The UN confirms the slow progress in creating climate resilient transport systems, despite growing understanding of climate risks to the sector, and recommends that climate risk assessment and adaptation planning for transport networks be incorporated into their respective national adaptation plans to fulfil international agreements, including the Paris Agreement (United Nations Climate Change, 2021).

Over half of the Paris Agreement signatory parties have referred to the protection of nature as an important motivator for adaption planning and have included NbS in the adaptation elements of their NDCs. The majority of these contain only high-level goals, however, and few detail explicit plans to deploy NbS in response to specific climate hazards (United Nations Environment Programme, 2021a, 2021b). Outputs from this research may therefore contribute to the wider body of work on the operationalisation of NbS, including practical measures to aid their deployment, in other sectors. The UN Climate Action Pathway – Transport 'Milestones towards 2050' includes the mainstreaming of NbS into transport infrastructure provision and improvement as a 'Pathway Action', however, there is no further detail on the concept included in their 2050 Vision nor suggestions as to how this may be achieved, the report instead focussing on decarbonisation of transport systems (United Nations Climate Change, 2021). It is acknowledged that without successful climate mitigation, adaptation efforts will also be insufficient to limit all risks associated with climate change (United Nations Environment Programme, 2021b). The benefits of rail as a low carbon emitting, climate change mitigating public transport mode are well documented (for example: International Union of Railways (2023a), Lawrence and Bullock (2022), The World Bank (2022)), and both the value of promoting rail as a sustainable transport mode and the contribution that this activity has in the operationalisation of NbS for rail remain consistent considerations in this thesis.

NbS have been confirmed as being incorporated into sectoral CCA planning processes, including those for infrastructure, however widescale approaches are deemed necessary to contribute sufficient ecosystem service provision to deliver the required levels of adaptation (United Nations Environment Programme, 2021a). Despite initial efforts towards the global goal on adaptation, there has been insufficient progress in implementing the support required for the populations and infrastructure that are already affected by the impacts of climate change (World Economic Forum, 2023). "Groundbreaking acceleration" is thus required in adaptation planning and implementation (United Nations Environment Programme, 2022, p. iii), and the following of best practices on these activities is therefore required to improve the effectiveness of CCA application (United Nations Environment Programme, 2022). The publication of this PhD research, in particular the development of case studies demonstrating NbS application in practice in the rail context, intended for distribution in the rail industry, will therefore be helpful in this regard.

The outputs of this study may potentially also support rail industry implementation of the Sendai Framework for Disaster Risk Reduction (DRR) (United Nations Office for Disaster Risk Reduction, 2015). The Sendai Framework highlights the importance for critical infrastructure, including transport infrastructure, to be resilient in order to remain safe and operational both during and after disasters to enable the provision of life-saving and essential services (United Nations, 2021b; United Nations Office for Disaster Risk Reduction, 2015). With regards to NbS, two of the Sendai Framework's 38 indicators relate to the use of green infrastructure being included “where relevant” in response to the ‘Reduce direct disaster economic loss in relation to global gross domestic product (GDP) by 2030’ and ‘Substantially reduce disaster damage to critical infrastructure and disruption of basic services, among them health and educational facilities, including through developing their resilience by 2030’ targets (United Nations Office for Disaster Risk Reduction, 2023), presenting further methods to encourage NbS uptake for DRR. Eco-DRR is proposed by the IUCN as an NbS approach that may reduce the likelihood of a natural hazard, such as an extreme weather event, turning into a societal disaster (Cohen-Shacham et al., 2016). In the railway context, Eco-DRR may reduce the risk to rail infrastructure from climate-related risks, e.g., reefs, mangroves and other coastal vegetation being used to help withstand track inundations from storm surges (Chapter 2).

As outlined in Chapter 1.2.2, the multiple and diverse technological range of separate railway infrastructure components means that there are many factors that need to be considered when conducting climate change risk assessments (CCRA) to identify and assess climate change impacts on rail infrastructure constituents, at both the individual component and collective system-wide levels, and similarly, when identifying and selecting suitable CCA measures. The complex, multidisciplinary nature of railway infrastructure and its interdependencies with other systems (such as electricity and telecommunication networks) therefore makes the undertaking of CCRA and selection of CCA measures particularly challenging for the rail industry. A ‘one size fits all’ CCA response may not be appropriate meaning that multiple, complementary and/or cumulative approaches may be required (Chapter 2). Chapter 3 and Chapter 5 confirm the importance of undertaking CCRA as part of the rail infrastructure management lifecycle, as the process instigates the CCA selection process which in turn presents an entry point for NbS as potential CCA measures.

The above confirms the need for investigating and promoting the implementation of CCA options for rail, and provides further justification on the value of researching the potential application of NbS in this regard and developing tools to support their uptake. The intention is that the outputs of this rail sector-specific research contribute to industry implementation of NbS concepts as CCA measures in response to the growing threat of climate change suffered by the industry.

1.4 Prior relevant research

This study brings together two bodies of literature: CCA for rail infrastructure, and the operationalisation of NbS. These areas of study have largely remained separate to date. Figure 1-4 illustrates the alignment of these two research topics amidst their respective broader research themes (i.e., climate change and NbS), and provides the context and relative volume of prior research conducted on each, i.e., extensive research has been conducted on the broad theme of climate change, less research has specifically investigated CCA, even less so for CCA for transport infrastructure, and only a very small proportion of research has considered CCA for rail infrastructure. Similarly, there has been significant growth in the body of research on NbS and on its operationalisation, with a lesser amount of literature on its implementation for CCA. As confirmed in the extensive literature review presented in Chapter 2, very few studies have been found to connect these two bodies of work to explore the application of NbS as CCA measures in the rail industry, demonstrating the originality of this research.

The literature reviews provided in Chapter 2 and Chapter 3 contain the theoretical backgrounds and previous relevant research on both the climate change and NbS themes included in Figure 1-4, in the context of this research. To avoid repetition with the content of later chapters, a timeline providing a condensed overview of the key milestones in the two themes is shown in Table 1-3.

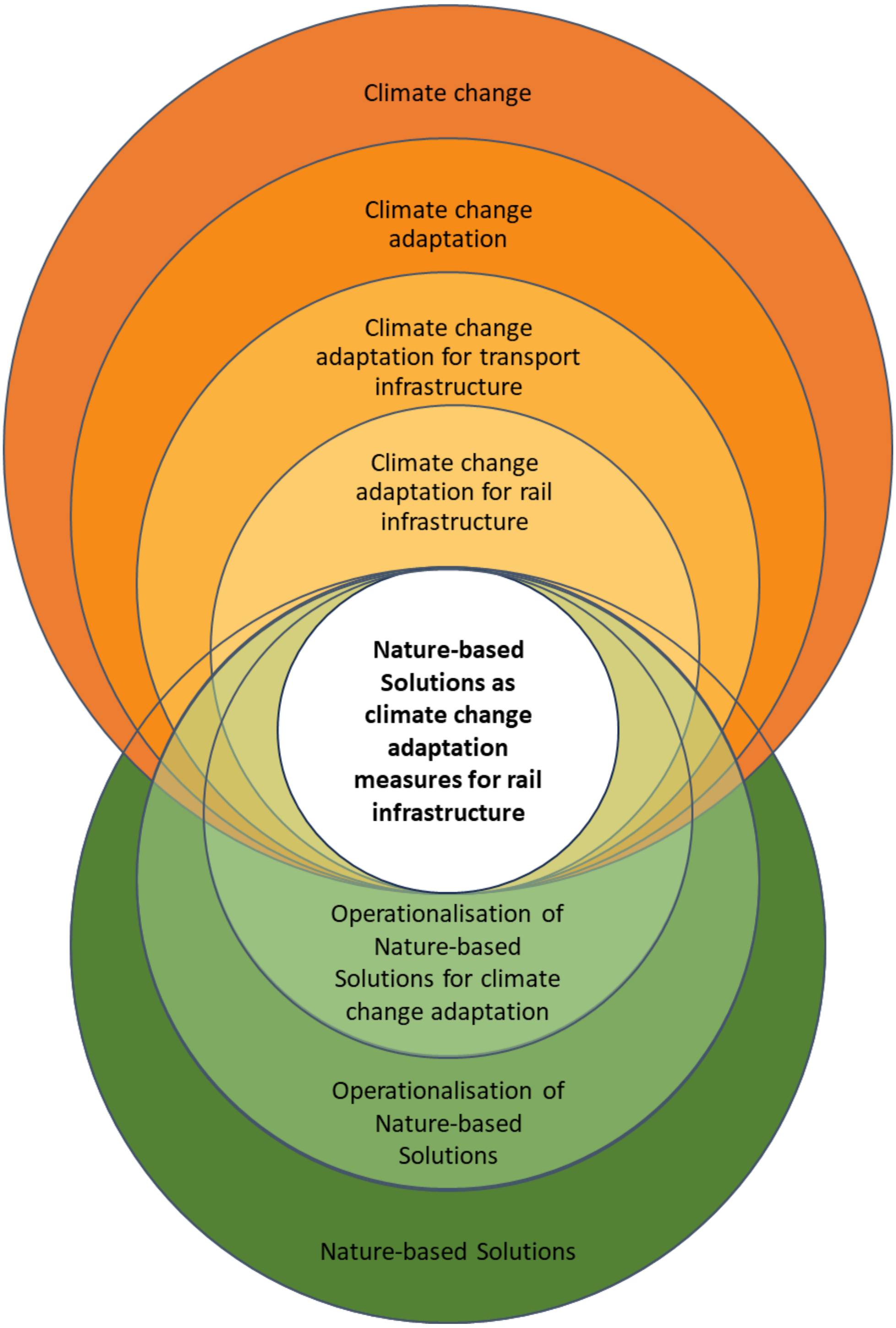

Figure 1-4 Context and relative volumes of relevant prior research (not to scale)

Table 1-3 Key research workstreams and outputs relating to climate change and NbS relevant to this thesis

Climate change theme	Year	Nature-based Solutions theme
The UN establish the IPCC to provide policymakers with assessments of the scientific evidence of climate change, its impacts and risks, and adaptation and mitigation options (IPPC, 2018).	1988	
The IPCC's third assessment reports that "Adaptation has the potential to reduce adverse effects of climate change and can often produce immediate ancillary benefits, but will not prevent all damages" (IPCC, 2021, p. 12).	2001	
Emergence of literature on climate change and CCA adaptation for transportation systems (Wang et al., 2020a).	2005	The Millenium Ecosystem Assessment defines ecosystem services as "the benefits that people obtain from ecosystems" which include provisioning, regulating, cultural, and supporting services (Millennium Ecosystem Assessment, 2005, p. v).
	2008	The World Bank Report 'Biodiversity, Climate Change and Adaptation: Nature-Based Solutions from the World Bank Portfolio' uses the term NbS with regards projects which incorporate biodiversity and conservation whilst delivering CCA benefits (The World Bank, 2008).
'Climate adaptation of railways - Lessons from Sweden' shares early rail-specific research on CCA (Lindgren et al., 2009).	2009	The IUCN position paper for the UNFCCC COP 15 promotes NbS as being integral to CCA and mitigation strategies, specifically referencing the NbS approach of 'Ecosystem-based adaptation' (EbA) (International Union for Conservation of Nature, 2009).
IPCC Special Report integrates the previously separate research	2012	

Climate change theme	Year	Nature-based Solutions theme
streams on climate science, climate impact, CCA and disaster risk management (IPCC, 2012).		
The Paris Agreement is adopted by 196 parties at the UN Climate Change Conference (COP21) (United Nations Framework Convention on Climate Change, 2015) – see Chapter 1.2.	2015	The European Commission define NbS as "living solutions inspired by, continuously supported by and using nature, which are designed to address various societal challenges in a resource-efficient and adaptable manner and to provide simultaneously economic, social, and environmental benefits" (Maes & Jacobs, 2015, p. 1).
	2016	The IUCN set a further definition for NbS (see Chapter 1.1) and present NbS as an umbrella concept comprising a variety of ecosystem-based interventions. They share an operational framework including general principles for implementing NbS (Cohen-Shacham et al., 2016).
2019 Increasing coverage of NbS CCA approaches observed in IPCC literature, with the Special Report on the Ocean and Cryosphere in a Changing Climate report promoting EbA as a response to climate-related impacts on oceans and the cryosphere (IPCC, 2019).		
	2020	The IUCN publish a Global Standard for NbS, aimed at providing a user-friendly, robust framework to verify, design and upscale the use of NbS (IUCN, 2020).
IPCC sixth assessment report confirms that human influence on the climate system has increased surface temperatures globally, and that human-induced climate change is impacting weather and climate extremes worldwide (IPCC, 2021).	2021	

Climate change theme	Year	Nature-based Solutions theme
	2022 NbS concepts are proposed as potential CCA measures for use on rail infrastructure (Blackwood et al., 2022) - see Chapter 2.	
CCA is observed across all sectors, including transportation, and all regions, however progress is not evenly distributed and CCA gaps exist. The worldwide response to the observed climate impacts and projected risks are deemed to be more urgent than previously reported (IPCC, 2023).	2023	
	2024 Launch of framework to apply NbS for CCA on rail infrastructure (Blackwood, 2024) - see Chapter 5.	

As confirmed in Chapter 2 and Chapter 3, the growth in research on the use of NbS in response to the impacts of climate change has, to date, largely focussed on its application in city and urban locations (Frantzeskaki et al., 2019), and a knowledge gap exists on NbS implementation for CCA on rail infrastructure, in both rural and urban settings. Meanwhile, the limited literature that exists on CCA measures for rail is described as "between too vague … and too detailed" (Wang et al., 2020b), and has been found to contain limited recommendations and details on rail-specific CCA responses (Armstrong et al., 2017; DeVinne et al., 2022). These observations provide further justification on the value of investigating the concept of NbS as CCA measures for rail, and for the development of rail sector specific guidance to enable the dissemination of NbS as credible, sustainable CCA measures.

Launched in 2020, the IUCN Global Standard for NbS is intended to provide users with a robust framework to design and verify NbS to deliver the desired outcomes in resolving societal challenges (IUCN, 2020). The Standard comprises of 8 criteria and 28 indicators, supported by the NbS Principles (Cohen-Shacham et al., 2019), to enable globally consistent measurement of the success of NbS interventions (IUCN, 2020). Rather than set rigid thresholds as to what NbS should achieve, the Standard has been designed to facilitate NbS implementation. However, the IUCN framework does not provide the level of detail or rail-specific examples that have been identified as being required for CCA implementation by the rail industry (Armstrong et al., 2017; DeVinne et al., 2022; Wang et al., 2020b). The Standard and its associated self-assessment tool may instead be applied alongside rail industry tools and guidance for CCA, e.g., as developed through this research, and/or upon completion of NbS installation, to measure its effectiveness against the standard's criteria and indicators, and to contribute to cross sector engagement and communications on NbS implementation using a common benchmark and terminologies (IUCN, 2020).

Recognising the significance of the problem posed to rail infrastructure by the impacts of climate change, as discussed in Chapter 1.3, the above synopsis of the existing, separate, research streams and bodies of work on the themes of CCA for rail infrastructure and the operationalisation of NbS confirms the merit of merging these workstreams, as undertaken in this thesis. Whilst other NbS implementation frameworks and tools exist, the complex nature of railway infrastructure, which comprises of multiple specialised and often highly technical engineering systems, combined with the rail-specific barriers to NbS implementation identified by Blackwood & Renaud (2022) (see Chapter 3), warrants the exploration of an industry bespoke tool to aid NbS deployment.

1.5 Research aims, questions and objectives

The overarching aim of this study is to assess the potential to implement NbS as CCA measures for rail, with a secondary, connected aim, of developing a framework for use by the rail industry to apply NbS as CCA. These aims are addressed through answering the following set of research questions (RQ):

RQ1: What is the evidence base on the use of NbS being implemented as CCA measures in the railway context?

RQ2: Are there NbS being used as CCA measures in rail which are not included in the literature?

RQ3: What are the challenges and barriers to the operationalisation of NbS as CCA measures for the rail industry?

RQ4: What could aid the operationalisation of NbS as CCA measures for the rail industry?

The responses to these research questions are addressed in the form of four research papers, each having been published in peer-reviewed journals, as presented in the next four Chapters of this thesis. Figure 1-5 shows the relationship between each research question and the paper(s) in which is it addressed.

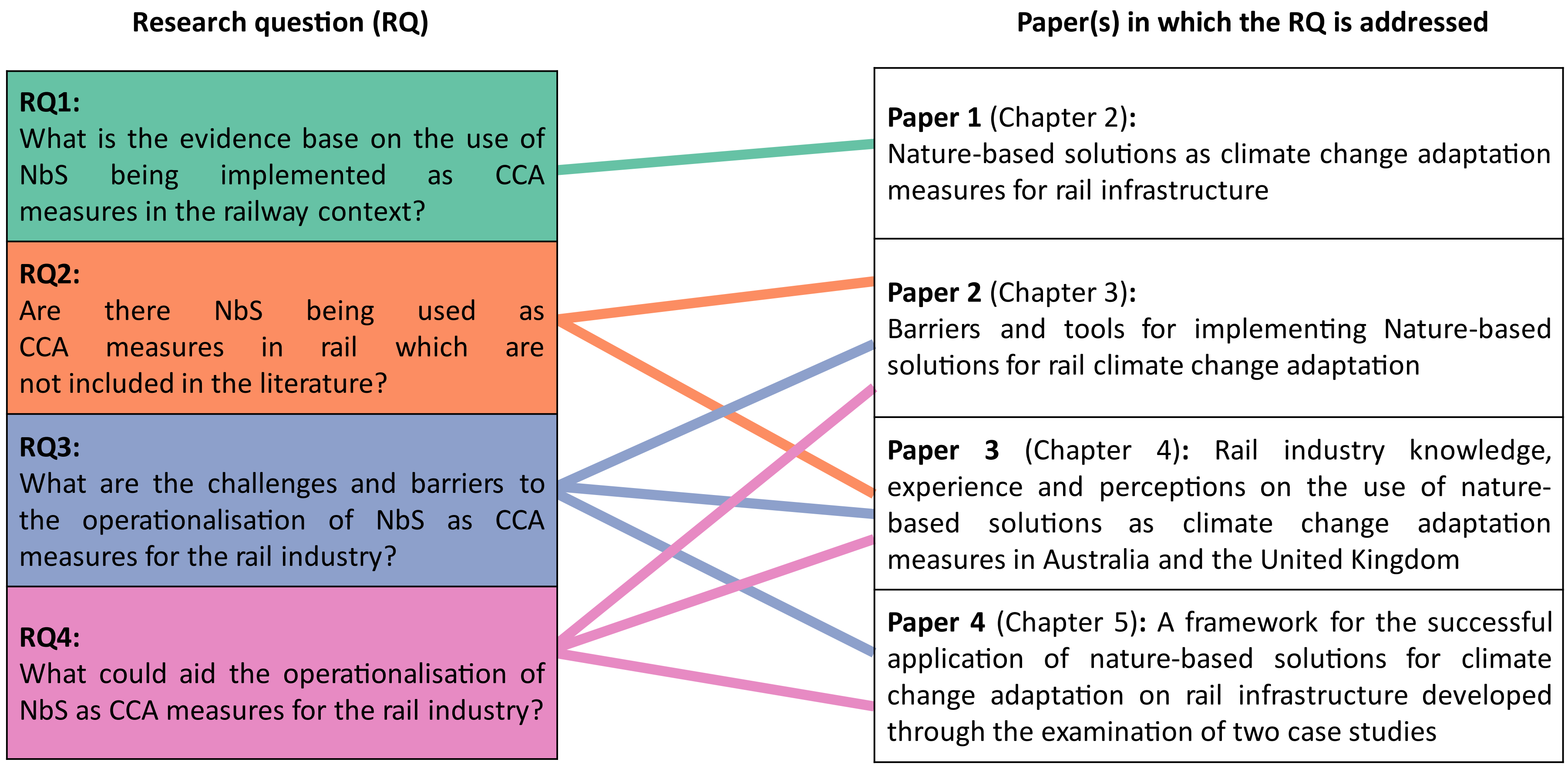

Figure 1-5 Research question coverage in the four research papers

To focus research activities towards achieving the overarching aims, research objectives, aligned with the research questions, were confirmed for each research paper, as shown in Table 1-4.

Table 1-4 Research objectives established for each research paper

Research Paper	Research objectives of each paper
Paper 1 (Chapter 2)**:** Nature-based solutions as climate change adaptation measures for rail infrastructure	To identify: • Published literature on the use of NbS in rail as CCA measures; • Examples of NbS in use in non-rail environments which may be transferable; and, • Gaps in current knowledge representing key areas that merit further research.
Paper 2 (Chapter 3)**:** Barriers and tools for implementing Nature-based solutions for rail climate change adaptation	To identify: • Barriers to the uptake of NbS on rail infrastructure and potential solutions to overcome these, including a proposed framework to incorporate NbS as CCA options in current rail infrastructure management practices.
Paper 3 (Chapter 4)**:** Rail industry knowledge, experience and perceptions on the use of nature-based solutions as climate change adaptation measures in Australia and the United Kingdom	To: • Engage with rail professionals to examine industry awareness on, examples of and attitudes towards the use of NbS as CCA measures for railway infrastructure.
Paper 4 (Chapter 5)**:** A framework for the successful application of nature-based solutions for climate change adaptation on rail infrastructure developed through the examination of two case studies	To: • Identify barriers and challenges encountered in, and aids to, the implementation of NbS in two cases, including any additional barriers to those identified in the literature and via earlier industry engagement; • Refine the 'Framework to incorporate NbS as CCA measures for rail infrastructure' (developed in Chapter 3) using learning from two cases, and engagement with rail professionals (Chapter 4) to provide an improved framework for use by the rail industry; and, • Contribute to education and knowledge on NbS use in rail for CCA by preparing two rail-specific case study examples.

1.6 Research approach

The problem-centred nature of this research, i.e., seeking practical CCA solutions to address real-world societal challenges, as detailed in Chapter 1.3, sees this research employ a pragmatist worldview (Creswell & Plano Clark, 2018). This approach focusses the primary importance on the research question as opposed to the methods used to answer it, and uses multiple data collection methods to investigate the problem being studied (Creswell & Plano Clark, 2018). Mixed research methods and techniques were therefore applied in this body of work to examine and respond to the four research questions from different angles, to aid the convergence of data and maximise the potential of answering the research questions, and therefore meet the research aims. As shown in Figure 1-5, the question set remained consistent across all four papers (although each paper did not address every research question) to support this triangulation of data. The research begins with a broad, exploratory approach, with findings from each paper shaping the focus and methodological details of subsequent work. For example, the framework presented in Chapter 3 was developed through inductive research and observations made in the literature. This was subsequently tested through the deductive confirmatory studies performed when examining the cases in Chapter 5. The methods applied to each paper, and the corresponding research questions they address, are shown in Figure 1-6. An outline of, and justification for, the methodological approaches utilised is provided below.

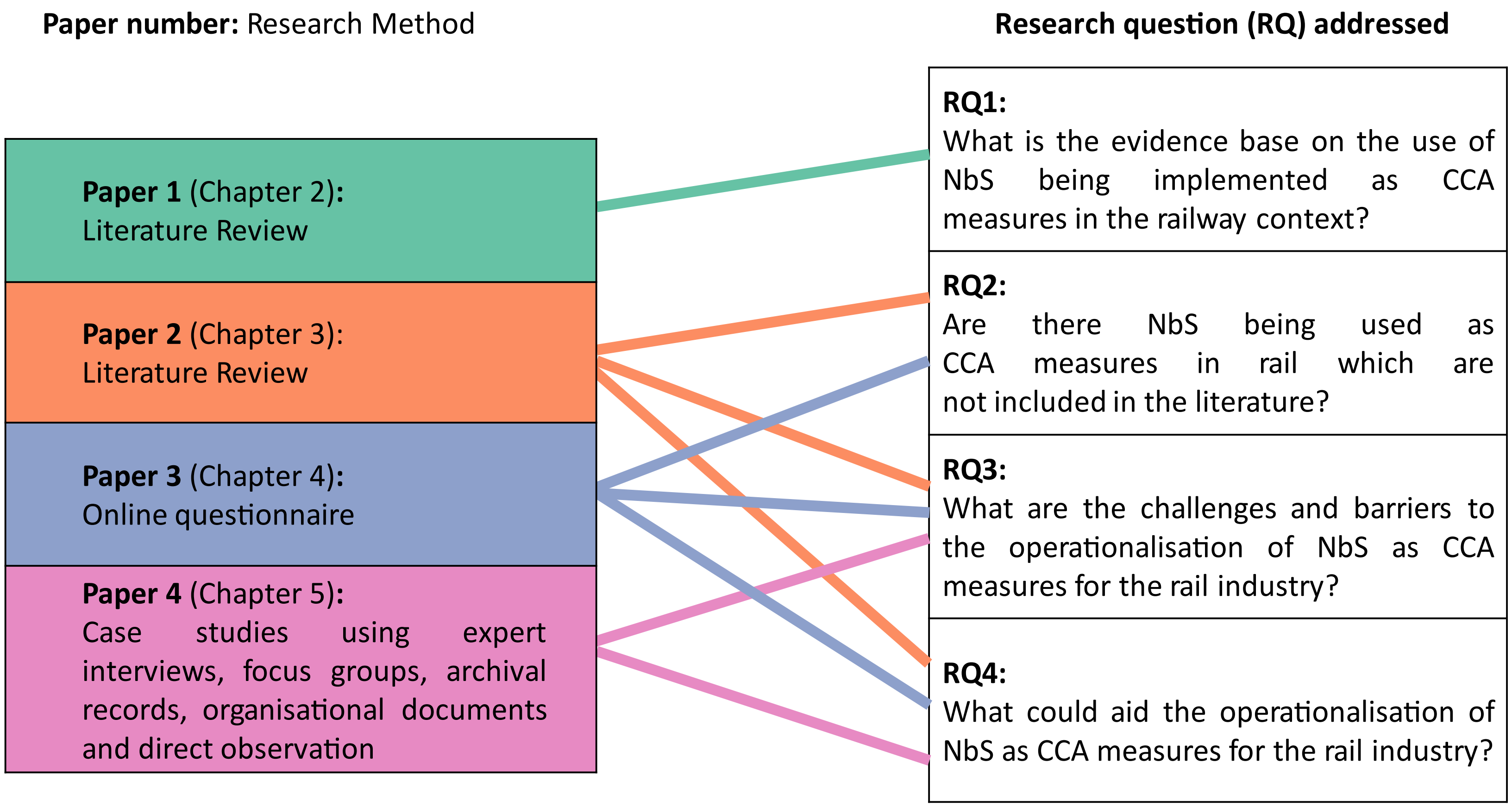

Figure 1-6 Research paper and methods used in response to research questions

Firstly, a literature review was undertaken to explore the evidence base on the use of NbS being implemented as CCA measures in the railway context. A systematic review (Xiao & Watson, 2019) was employed to determine the relevance and validity of the evidence found in the literature, with a snowball technique (Wohlin, 2014) being used to inform further review and literature searches until saturation was reached. The outputs enabled the quantification and visualisation of the review findings to help confirm and summarise the conclusions (Lewis-Beck et al., 2004a) for RQ 1, whilst also helping to provide direction for answering subsequent research questions (Creswell & Creswell, 2018). The narrative provided in Chapter 2 presents the current state of knowledge on the general topic of CCA impacts on rail infrastructure, setting the scene for the study and showing how it fits into the existing literature (Lewis-Beck et al., 2004a). In an original contribution to knowledge, Chapter 2 introduces to the literature the concept of the potential to use NbS as CCA measures in the rail context, and proposes potential NbS concepts suitable for application on rail infrastructure.

Due to the extremely limited information on NbS being used in rail found through the Chapter 2 literature review, the data sources utilised in Chapter 3 included the broader themes of general vegetation management (as opposed to only vegetation labelled as 'NbS'), and the operationalisation of CCA and NbS beyond the rail infrastructure scope. The low number of examples of NbS being used in rail identified confirms the extensive knowledge gaps on this topic and validates the original contribution to knowledge made by this research.

The use of an online questionnaire as the primary measurement tool to inform Chapter 4 provided the opportunity to collect both qualitative and quantitative data from international participants, enabling them to contribute responses to RQs 2, 3 and 4, in a simultaneous singular approach. This parallel method, as opposed to an explanatory sequential approach (Lewis-Beck et al., 2004b; Tashakkori & Teddlie, 2014), allowed the provision of responses to both exploratory (generally qualitative) and confirmatory (generally quantitative) questions (Lewis-Beck et al., 2004b). From a practical and logistical perspective, this approach aided the efficiency of administering the questionnaire, the online survey format providing a global reaching vehicle to efficiently gather data. A web-based questionnaire allows participants to respond in their own time, once, i.e., reducing respondent burden, and with less perceived pressure to reply, as may be the case in an interview. The online survey format provides time for participants to gather their thoughts, recall memories and look up examples, thereby reducing recall error and adding to the data quality and richness. Whilst the majority of survey participants were based in the UK and Australia, meaning it is unlikely that language barriers would have posed a problem, writing the survey questions in English will have eased any translation where required, and prevented any misunderstanding that may take place in spoken interviews.

Purposive sampling was used to generate as much detail as possible from survey participants to maximise the likelihood of answering the research questions. The participants targeted were those based in roles named in the literature as being key stakeholders who should be involved in CCRA for railway infrastructure. Noting that purposive sampling relies heavily on the expert judgement of the researcher (Tashakkori & Teddlie, 2014), the selection of suitable participants was guided by the author's professional judgement, based on having circa 20 years' experience in railway infrastructure sustainability, including CCA. The questionnaire was pretested to make sure the questions were easy for people to comprehend and answer, and to help reduce acquiescence (Krosnick & Presser, 2010). Pre-testing was also intended to help prevent 'I don't know' responses due to people not understanding the question. Following that step, no significant changes were identified as being required.

Questions were funnelled, moving from the general to specific, and screening questions were grouped at the beginning to avoid later fatigue, or prevent subsequent false answers and mitigate lengthier contingent questions (Krosnick & Presser, 2010). The use of closed questions enabled the quantitative measurement and description of trends, attitudes and opinions on the use of NbS as CCA measures in rail, whilst qualitative data was gained by setting open ended questions without pre-determined responses (Creswell & Creswell, 2018), adding depth to the survey results (Krosnick & Presser, 2010). Qualitative research is deemed especially useful when dealing with a new topic or a subject that has not been addressed with a certain sample or group of people (Creswell & Creswell, 2018), as is the case with this research. Given the lack of existing literature on the use of NbS in rail, and that the use of qualitative data alone is often not efficient to get access to all dimensions of a research question (Lewis-Beck et al., 2004b), the strengths of both quantitative and qualitative research were applied in order to maximise exploration and understanding (Creswell & Creswell, 2018), the latter being deemed to provide more reliable and valid measurement than closed items (Krosnick & Presser, 2010).

5-point Likert scales were used for attitude measurement; this response scale is recommended for items signifying relative response levels (Boateng et al., 2018), where the intended meaning of the scale can be easily interpreted with words. Scaled descriptors can become less clear over larger scales, whilst a moderate scale (in this instance five) provides higher validity than a shorter point scale (Krosnick & Presser, 2010) (i.e., of only two or three). It is acknowledged that providing midpoint and 'I don't know' response options may have encouraged satisficing, however, because NbS are a new concept, respondents may not have sufficient knowledge or information on which to form an opinion (Krosnick & Presser, 2010). Further, the provision of midpoints has been found to improve the reliability while not affecting the validity of attitude measurements ratings (O'Muircheartaigh & Krosnick, 2000), suggesting that offering midpoints will help to increase data quality. Data was collected following the granting of Ethics approval by the University of Glasgow's College of Social Sciences Research Ethics Panel. The provision of study findings was offered to survey participants upon their request. It was confirmed to all participants prior to commencing the survey that all responses will be treated anonymously, this can help to avoid social desirability responses bias (Grimm, 2010). As the survey was distributed by a sustainability professional this may have introduced an element of social pressure, however, and may therefore have prompted responses that are deemed more favourable.

Chapter 5 used case study research to explore NbS being used as CCA in rail, and to test the appropriateness of the literature-based framework developed in Chapter 3, on two live railway infrastructure cases. It involved the detailed, in-depth data collection of real-life examples using multiple sources of information (Creswell & Poth, 2018, p. 96) to maximise the potential to address the research questions and aid data triangulation. A case study protocol was developed, as recommended by Yin (2018), to guide the design, undertaking and recording of the case study research. A 'Case Comparator' spreadsheet was also developed to track the data sourced for each case, and then compare how the information obtained for each case addressed the research question.

Conducting two case studies, comparing and contrasting the suitability of the proposed framework against two locations with different contexts, geographies and climates, strengthens arguments on the generalisability of the proposed framework for the implementation of NbS as CCA measures in rail. Although the inclusion of evidence from further additional cases would strengthen findings (Herriott & Firestone, 1983), a lack of suitable examples of the live application of NbS as CCA in rail (as confirmed in Chapter 2), combined with potential author conflict of interest preventing the use of other cases, made it difficult to source further suitable locations. Regardless, the conclusions gained from two independent cases are more powerful than those gained through the examination of a single case (Yin, 2018); this is particularly valid since the two cases represent contrasting situations.

The case study data sources include semi-structured interviews and focus groups with rail industry professionals involved in the planning, design, construction and operation of the infrastructure featured in each case. A question set was drafted for the interviews and focus groups to provide a guide for these sessions to ensure consistency, and to maintain direction towards addressing the study's research questions and objectives. The semi-structured nature of the interviews and focus groups allowed the collection of qualitative data targeted to the research questions, whilst allowing participants to express themselves freely. Additional questions emerged to those prepared in the predetermined question set based on interviewer and interviewee dialogue, a benefit of not applying a rigid, fixed interview format (DiCicco-Bloom & Crabtree, 2006). Data was collected following the granting of a second Ethics approval by the University of Glasgow's College of Social Sciences Research Ethics Panel. The recordings from the interviews and focus groups were transcribed and analysed for common themes (Krueger & Casey, 2015). Due to the relatively small volume of data these were compiled in an Excel spreadsheet. The provision of study findings was offered to interviewees and focus group participants upon their request.

In undertaking this pragmatic research that seeks to address a real-world challenge in an industry in which the author possesses significant experience, there has been a danger of introducing biases. To avoid promoting any preconceived stance (Yin, 2018) the author may have on the potential success (or otherwise) of the implementation of NbS as CCA for rail infrastructure, a rigorous literature search protocol was applied in Chapter 2 to identify and report upon all relevant data. The outputs were then used in Chapter 3 to present both the pros and cons of the use (or potential use) of NbS in the rail environment. To further avoid confirmation bias (Centre for Evidence-Based Medicine, 2023), the case studies detailed in Chapter 5 record and disclose all relevant available data from multiple sources. Care was taken in the choosing of suitable cases to avoid selection bias, and ensure no conflict of interest.

1.7 Outline of the thesis

This thesis consists of six chapters. Following this introductory chapter, the next four chapters contain the four research papers, as published in their respective peer-reviewed journals and without any additional commentary:

Chapter 2: Nature-based solutions as climate change adaptation measures for rail infrastructure.

Chapter 3: Barriers and tools for implementing Nature-based solutions for rail climate change adaptation.

Chapter 4: Rail industry knowledge, experience and perceptions on the use of nature-based solutions as climate change adaptation measures in Australia and the United Kingdom.

Chapter 5: A framework for the successful application of nature-based solutions for climate change adaptation on rail infrastructure developed through the examination of two case studies.

These chapters are followed by a conclusion that summarises the outcomes and overall implications of the research, and an evaluation of the framework against global NbS principles and standards. The Supplementary Information relevant to each published paper is included as Appendices at the end of this document, prior to a bibliography of all references.

Chapter 2 Nature-based solutions as climate change adaptation measures for rail infrastructure

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Author Contributions:

Conceptualization and Methods: LB, FGR & SG; Review & analysis: LB; Writing—original draft preparation: LB; Writing—review and editing: LB, FGR & SG; Supervision: FGR &SG.

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Abstract:

The transport sector fulfils crucial economic and social functions with railways being instrumental in the safe, efficient, and reliable movements of people to their destinations and goods to market. One of the most critical vulnerabilities in the railway transport system is the low flexibility of both infrastructure and operations in the event of disturbances including those caused by extreme weather events such as floods, droughts, storm surges and temperature extremes. With the frequency and intensity of such events being projected to increase, the failure to proactively consider the impacts of a changing climate on new and existing infrastructure raises the possibility of increased service disruption and adverse economic impacts as climate change progresses. Nature-based solutions (NbS) present long-lasting, cost-effective and environmentally sustainable climate change adaptation (CCA) options. However, as an effective alternative or complement to grey (engineered) solutions, they are still in their infancy, especially within the railway sector. To date very few studies have investigated the role of NbS for CCA in the railway transport system. Recognising the importance of the rail industry's need to adapt its infrastructure to accommodate current weather extremes and a changing climate, this review paper examines NbS being used as CCA measures both in the rail context, and in non-rail contexts which may be transferable to the rail sector. Our review demonstrates that there are significant knowledge gaps that may hinder the uptake of NbS in the rail environment which warrant further research to support the inclusion of NbS as viable CCA options for rail infrastructure. Better understanding of these issues is required for the development of rail sector specific guidance and will enable better design, implementation, and dissemination of NbS as credible alternatives or complements, and more sustainable CCA measures.

Keywords: climate change adaptation, rail infrastructure, nature-based solutions, green infrastructure, ecosystem-based adaptation, ecosystem-based disaster risk reduction

2.1 Climate change impacts on rail

The transport sector is almost continuously subjected to hydro-meteorological hazards (HMH) which impact upon the efficiency of its operations (Jaroszweski et al., 2010; Thornes, 1992), with railway infrastructure being particularly exposed and vulnerable to weather (Lindgren et al., 2009; Network Rail, 2015). HMH are atmospheric, hydrological and oceanographic phenomena that may cause significant impact on human life and infrastructure; examples include floods, droughts, storm surges and temperature extremes (Debele et al., 2019; United Nations Office for Disaster Risk Reduction, 2021). Human influence on the climate system is now an established fact, with human-induced climate change increasing global surface temperatures and subsequently affecting many weather and climate extremes in every region across the globe (IPCC, 2021). The duration, magnitude, scale, and frequency of climate-related risks are projected to increase and worsen (IPCC, 2012) meaning that the observed "extreme" weather of today could become the "normal" weather of tomorrow (Nolte et al., 2011). Higher average temperatures, higher sea and precipitation levels, more frequent and severe adverse hydro-meteorological events create specific risks for railway assets (Marteaux, 2016). The exposure of railway infrastructure to these extremes, unaccounted for in its original design, may shorten its life span, pose a physical threat to the safe operation of rail services, and increase maintenance and operation costs (Palko & Lemmen, 2017). Climate change presents a complex global challenge in managing the resilience of transport infrastructure (Davies et al., 2014) with railways needing not only to withstand current extreme weather conditions and recover from these quickly, but to also be able to continue operating in future conditions which are today regarded as extreme (Nolte, n.d.).

Table 2-1 presents a comprehensive overview of the detrimental impacts to railway infrastructure (Column B) caused by a range of HMH (Column A). Rail infrastructure design, construction and operational activities are typically categorized by engineering discipline, for example Track, Signalling, Overhead Wiring, Railway Civils (concerning trackside embankments, cuttings, drainage systems and vegetation) and Railway Structures (track-carrying structures including bridges, tunnels, viaducts and culverts). This study does not consider railway buildings e.g., stations or signal boxes. Figure 2-1 shows that of the seven HMH considered, high temperatures present the most extensive hazard, with the potential to impact all rail infrastructure engineering disciplines.

Table 2-1 Key hydro-meteorological hazards to railway infrastructure, current climate adaptation measures currently in use and potential nature-based alternatives and/or complements

Table format adapted from Network Rail (2015), Nolte (n.d.) and Stipanovic Oslakovic et al. (2013)

A	B	C	D
Hydro-meteorological hazard	**Rail infrastructure impact**	**Current adaptation measures**	**Potential NbS alternative and/or complements***
High temperatures	Rail buckling and/or associated misalignment problems (Armstrong et al., 2017; Fisk et al., 2019; Hooper & Chapman, 2012; Marteaux, 2016; Nolte, n.d.; Quinn et al., 2018; Wang et al., 2020b; Wang et al., 2020c)	• Change rail installation procedure to increase temperature threshold for thermal expansion (Marteaux, 2016; Network Rail, 2020a; Palko & Lemmen, 2017) • Replacement of jointed track with continuously welded rail (Network Rail, 2020a) • Upgrade timber switches and crossings to concrete (Network Rail, 2020d) • Painting rails white in areas of known high risk to thermal expansion in direct sunlight (Network Rail, 2020a)	• Green corridors • Vegetation shading • Vegetation management – specific species selection
	Expansion of moveable assets such as swing bridges hindering operation (Hooper & Chapman, 2012; Marteaux, 2016)	• Sprinkler systems (Network Rail, 2020a) • Replacement of bridges with heat resistant materials with lower thermal expansion coefficients (Network Rail, 2020a)	
	General increase in failure rate of assets in high temperatures (Network Rail, 2015; Nolte, n.d.; Palko & Lemmen, 2017)	• Use of coolers, fans and air conditioning to improve tolerance of signalling equipment (Doll et al., 2013; Network Rail, 2020d; Palko & Lemmen, 2017) • Double-skinned equipment casing to assist cooling (Network Rail, 2020a) • Sun hoods to deflect heat (Network Rail, 2020d)	

A	B	C	D
Hydro-meteorological hazard	**Rail infrastructure impact**	**Current adaptation measures**	**Potential NbS alternative and/or complements***
	Sagging of the overhead line equipment (Armstrong et al., 2017; Marteaux, 2016; Quinn et al., 2018)	• Removal of fixed termination overhead line equipment (Network Rail, 2020a) • Improved balance weight and head span technologies (Network Rail, 2020d)	
	Increased fire risk (Fisk et al., 2019; Lin et al., 2011)	• Vegetation management along tracks (Doll et al., 2013; Lindgren et al., 2009) • Establishment of tree-free zones in rail corridor (Lindgren et al., 2009)	
	Permafrost degradation causing heaving, sinkholes, potholes and settlement (Hooper & Chapman, 2012; Palko & Lemmen, 2017)	• Clearing snow to preserve permafrost stability (Palko & Lemmen, 2017) • Installation of thermosyphons, air ducts, awnings and 'cooled roadbeds' using crushed rocks (Jin et al., 2008; Ma et al., 2011)	
Low temperatures	Rail breaks, cracks and/or associated misalignment problems (Network Rail, 2015)	• Change rail installation procedure to increase temperature threshold for thermal expansion (Davies et al., 2014)	• Green corridors • Vegetation shading • Bioengineering and biotechnical stabilisation • Green walls and embankment • Natural drainage solutions
	Snow blocking tracks (Doll et al., 2013; Network Rail, 2014), obscuring signals and preventing train contact with conductor rails on 'third rail' networks (Network Rail, 2020a)	• Use of signal hoods to prevent build-up of snow (Network Rail, 2020a) • Potential heating of conductor rails (Network Rail, 2020a) • Points heater installation (Network Rail, 2020a)	
	Ice-jam flooding damaging infrastructure, particularly bridges (Palko & Lemmen, 2017)	• Installation of dams, ice booms, ice-retention structures, dykes, or various channel modifications (Beltaos et al., 2000)	

A	B	C	D
Hydro-meteorological hazard	**Rail infrastructure impact**	**Current adaptation measures**	**Potential NbS alternative and/or complements***
	Tree and branch falling onto tracks due to snow loading (Marteaux, 2016; Network Rail, 2015)	• Establishment of tree-free zones in rail corridor (Lindgren et al., 2009)	
	Icefalls in tunnels, under bridges and other structures causing damage or derailment of trains (Doll et al., 2013; Network Rail, 2015)	• Review of drainage provisions for bridges and tunnels (Network Rail, 2020a) • Capping of tunnel shafts (Quinn et al., 2017)	
	Frost heave of track bed and earthworks (Network Rail, 2015; Palko & Lemmen, 2017)	• Installation of geothermal piles (Akagawa et al., 2017)	
	Freeze-thaw damage to rock cuttings and associated landslides (Doll et al., 2013; Hooper & Chapman, 2012; Network Rail, 2015)	• Rock slope stabilisation and protection (Palko & Lemmen, 2017)	
High precipitation	Increased risk of earthworks failure and landslides in wet weather (Armstrong et al., 2017; Fisk et al., 2019; Hooper & Chapman, 2012; Marteaux, 2016; Network Rail, 2015; Nolte, n.d.; Wang et al., 2020a; Wang et al., 2020c)	• Planting of ‘protection forests’ (Doll et al., 2013) • Slope stabilisation programmes including installation of gabion walls, soil nails and sheet piles (Network Rail, 2020a) • Counterfort drains in slopes and crest drain refurbishment (Network Rail, 2020a)	• Bioengineering and biotechnical stabilisation • Green walls and embankments • Natural drainage solutions • Protection forests
	Increased risk of bridge scour arising from flood events (Armstrong et al., 2017; Doll et al., 2013; Marteaux, 2016; Network Rail, 2015; Nolte, n.d.; Wang et al., 2020a)	• Bridge scour protection programmes (Network Rail, 2020a)	

A	B	C	D
Hydro-meteorological hazard	**Rail infrastructure impact**	**Current adaptation measures**	**Potential NbS alternative and/or complements***
	Failure of other structure supports due to increased risk of scour (Armstrong et al., 2017; Network Rail, 2015; Nolte, n.d.; Wang et al., 2020a)	• Scour protection programmes (Network Rail, 2020a)	
	Standing water fouling track ballast weather (Armstrong et al., 2017; Hooper & Chapman, 2012; Palko & Lemmen, 2017; Wang et al., 2020a)	• Expanding drainage capacity for infrastructure including culvert size, design for new flood event thresholds, (Network Rail, 2014; Palko & Lemmen, 2017) • Increasing maintenance including clearing debris from culverts to reduce flooding (Palko & Lemmen, 2017) • Installation of emergency culvert and aboiteaux (Palko & Lemmen, 2017) • Installation of pumped drainage solutions (Network Rail, 2020a) • Reno mattresses (Network Rail, 2020a)	
	Lahars causing structural damage to infrastructure (Doll et al., 2013)	• Installation of containment channels and dikes (Pierson et al., 2014) • Revetments using riprap, gabion mattresses and concrete facings (Pierson et al., 2014) • Anchors, geogrids and micro-piles (Pierson et al., 2014)	

A	B	C	D
Hydro-meteorological hazard	**Rail infrastructure impact**	**Current adaptation measures**	**Potential NbS alternative and/or complements***
Low precipitation	Increased risk of earthworks failures due to desiccation (Hooper & Chapman, 2012; Marteaux, 2016; Network Rail, 2015; Nolte, n.d.)	• De-vegetation programmes (Network Rail, 2020a) • Re-ballasting and tamping interventions (Network Rail, 2020a)	• Bioengineering and biotechnical stabilisation • Green walls and embankments
High winds	Increased risk of leaf fall leading to low track adhesion (Network Rail, 2015)	• De-vegetation programmes (Network Rail, 2020a) • Establishment of tree-free zones in rail corridor (Lindgren et al., 2009; Network Rail, 2020a)	• Vegetation management - specific species selection • Shelterbelts
	Damaged trees and debris falling onto track (Fisk et al., 2019; Network Rail, 2020s; Nolte, n.d.; Wang et al., 2020a)	• De-vegetation programmes (Network Rail, 2020a) • Establishment of tree-free zones in rail corridor (Lindgren et al., 2009)	
	Excessive wind loading on structures such as masts and towers (Network Rail, 2015; Wang et al., 2020a)	• Strengthening of existing equipment, build in resilience to design of new equipment (Dora, 2012) • Improved overhead wire tensioning systems (Baxter, 2015)	
	Significant wave formation causing damage to the track (Network Rail, 2020a; Palko & Lemmen, 2017)	• Elevate infrastructure (Network Rail, 2020a; Palko & Lemmen, 2017) • Improved flood defences (Network Rail, 2020a)	
	Increased risk of damage to bridges in high winds (Network Rail, 2015)	• Use of guide vanes (Nasr et al., 2020)	

A	B	C	D
Hydro-meteorological hazard	**Rail infrastructure impact**	**Current adaptation measures**	**Potential NbS alternative and/or complements***
		• Install damping devices (Beygi, 2015; Nasr et al., 2020)	
Lightning and electrical storms	Damage to buildings and structures from lightning strikes (Marteaux, 2016; Network Rail, 2015)	• Install lightning conductors (Quinn et al., 2017) • Fitment of surge protection (Network Rail, 2020d)	• Vegetation management – specific species selection
	Forest fires cause by lightning (Palko & Lemmen, 2017)	• Establishment of tree-free zones in rail corridor (Lindgren et al., 2009)	
	Damage to lineside trees from lightning strikes (Network Rail, 2015)		
High sea levels and storm surges	Coastal erosion of earthworks, structures and track (Armstrong et al., 2017; Fisk et al., 2019; Hooper & Chapman, 2012; Marteaux, 2016; Network Rail, 2015; Nolte, n.d.)	• Elevate infrastructure (Palko & Lemmen, 2017) • Install rock armour (Network Rail, 2020a)	• Bioengineering and biotechnical stabilisation • Dune and beach restoration • Natural drainage solutions • Reefs and mangroves • Saltmarshes and coastal vegetation
	Seawater inundation of earthworks, structures and track (Fisk et al., 2019; Hooper & Chapman, 2012; Network Rail, 2015; Wang et al., 2020a; Wang et al., 2020c)	• Elevate infrastructure (Network Rail, 2020a; Palko & Lemmen, 2017) • Raise sea walls (Network Rail, 2014)	
	Damage to sea walls (Marteaux, 2016; Network Rail, 2015)	• Flood defences designed for new flood event thresholds (Network Rail, 2020a) • Install rock armour (Network Rail, 2020a) • Raise sea walls (Network Rail, 2014)	

*Sourced using the research protocol and findings presented in subsequent sections

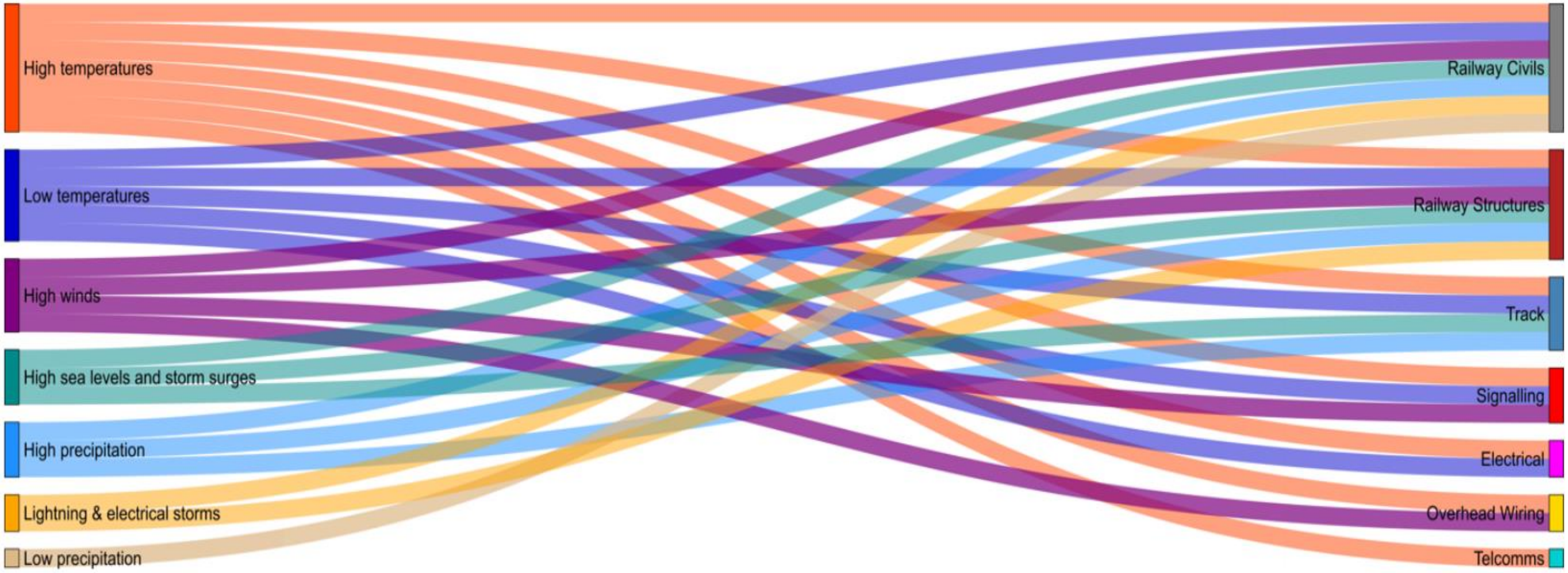

Figure 2-1 Relationships between hydro-meteorological hazards and rail infrastructure categorised by engineering discipline

2.2 Climate change adaptation options for rail

The Intergovernmental Panel on Climate Change defines adaptation as "the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities" (IPCC, 2014, p. 5). Adaptation to climate change can incorporate a range of potential actions (Jones et al., 2012). The prevailing approach across the world has involved a combination of direct, engineered (or 'grey') interventions such as sea walls and levees, and indirect (or 'soft') solutions (Seddon et al., 2020b) such as policies, planning and management approaches including early warning systems for extreme weather (Palko & Lemmen, 2017). This review considers the physical, infrastructure-based adaptation options for railways.

Column C of Table 2-1 details the current engineered adaptation measures in use on rail infrastructure in response to climate-related impacts; data is sourced from a range of academic and grey literature (non-academic publications and reports), as at September 2021. Other than a small number of procedural changes to current practices (e.g., vegetation clearance and changes to rail installation techniques), the majority of measures in place are grey-engineered solutions. This is consistent with research by Stamos et al. who, after clustering into categories suggested climate adaptation measures for transportation modes, including rail, found most of their options to be 'technical' (2015). They claim that this is "to be expected, as such solutions are often more straightforward in terms of implementation, compared to organisational or legislative measures, where potential bureaucracy may result in slow reaction times" (Stamos et al., 2015, pp. 6-7). This may not necessarily be systematically true however, as whilst some adaptation options are technically relatively easy to implement, the social and institutional complexity that their implementation brings about can prove much more difficult to address (De Bruin et al., 2009).

2.3 Nature-based Solutions

Adaptation to climate change can include a variety of potential actions. Along with 'soft' and 'grey' interventions, there is widespread recognition that nature-based (or ‘green’) solutions can complement these approaches (Seddon et al., 2020b). Nature-based Solutions (NbS) are defined by the International Union for Conservation of Nature (IUCN) as “actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits” (Cohen-Shacham et al., 2016, p. 4). The ecosystem regulating services provided to society by NbS include the regulation of climate, water, erosion and natural hazards (Cohen-Shacham et al., 2016; Millennium Ecosystem Assessment, 2005). The United Nations (UN) recognise the contribution NbS provide to the 2030 Sustainable Development Goals (SDGs) through their support to these vital ecosystem services, and explain how NbS further underpin the SDGs by enabling access to fresh water, improved livelihoods, healthy diets and food security from sustainable food systems (United Nations Global Compact, 2019), whilst the IUCN advocates the powerful contribution that NbS can make in reducing the risks posed to society by climate change and natural hazards (Cohen-Shacham et al., 2016).

Although people have used the natural environment to cope with climatic variability for millennia (Jones et al., 2012), the NbS concept has gained increasing attention at national and international levels in the last decade or so because of the urgent need to find practicable, flexible, cost-effective CCA interventions that reduce vulnerability under rapid anthropogenic climate change (Cohen-Shacham et al., 2016; Jones et al., 2012) while improving sustainable livelihoods and protecting natural ecosystems and biodiversity (Mittermeier et al., 2008 in Cohen-Shacham et al., 2016). Examples include:

- Developing green infrastructure in urban environments (e.g., green walls, roof gardens, street trees, vegetated drainage basins) to improve air quality, support wastewater treatment, and reduce stormwater runoff and water pollution as well as improve the quality of life for residents; and,
- Using natural coastal infrastructure such as barrier islands, mangrove forests and oyster reefs to protect shorelines and communities from coastal flooding and reduce the impacts of sea-level rise (Cohen-Shacham et al., 2016).

NbS is broad in definition and scope (Kabisch et al., 2017). It is considered as an umbrella concept that covers a range of ecosystem-based approaches, all of which address societal challenges (Cohen-Shacham et al., 2016). Of the NbS categories and approaches proposed by Cohen-Shacham et al., three lend themselves particularly well to climate change impacts on railway infrastructure: Ecosystem-based adaptation (EbA), Green Infrastructure (GI) and Ecosystem-based disaster risk reduction (Eco-DRR) (2016), as explained below.

The Convention on Biological Diversity (CBD) defined EbA in 2009 as “the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people adapt to the adverse effects of climate change” (IUCN, 2009, p. 1). EbA focuses primarily on CCA, with adaptation efforts leading to co-benefits that extend beyond adaptation (Kabisch et al., 2017); for example, the rehabilitation of mangroves to protect coastlines [and their railways] from increased storms and floods whilst supporting biodiversity conservation (Oliver et al., 2012). EbA is generally deployed in the form of targeted management, conservation and restoration activities (Jones et al., 2012), which use ecosystem services purposively to increase human societies’ resilience in the face of climate change (Oliver et al., 2012).

Green Infrastructure (GI) is a “strategically planned network of natural and semi-natural areas with other environmental features designed to deliver a wide range of ecosystem services such as water purification, air quality, space for recreation and climate mitigation and adaptation” (European Commission, 2021). GI includes ecosystems that perform many of the same functions as conventional grey infrastructure, such as water collection, purification, storage, and conveyance (Dalton & Murti, 2013 in (Cohen-Shacham et al., 2016)). Compared to EbA, the connection between GI and CCA is less direct (Kabisch et al., 2017); however, the infrastructure services are provided by ecosystems that deliver multiple other benefits, including climate adaptation. This could therefore present GI as a strong NbS candidate to be incorporated into, or potentially even replace, traditional mono-functional grey infrastructure (Kabisch et al., 2016) currently used in the rail environment. Whilst GI and the Natural Infrastructure (NI) approach are often used interchangeably (Bertule et al., 2014; Cohen-Shacham et al., 2016) their application tends to refer to different contexts and scales. In particular, NI is used only at a landscape scale – a level which is likely to be beyond the physical and jurisdictional boundaries that rail infrastructure owners can influence. GI is therefore more directly relevant to railway-specific CCA interventions, however NI is not excluded from this research due to the complementary nature of the multiple ecosystem approaches which contribute to the NbS concept.

Ecosystem-based disaster risk reduction (Eco-DRR) may also have a role to play in terms of reducing risks to rail infrastructure from current and future climate-related hazards, for instance at locations prone to landslides, flood or storm surges. Eco-DRR is "the sustainable management, conservation, and restoration of ecosystems to reduce disaster risk, with the aim of achieving sustainable and resilient development" (Renaud et al., 2016, p. 4). Although this definition does not include a reference to climate change, it is considered that Eco-DRR contribute to CCA as climate change is considered to be a risk amplifier now and, in the future [*ibid*]. Several initiatives are described interchangeably as either Eco-DRR or EbA, with Renaud et al. slightly adapting the Eco-DRR definition to account for CCA, with Eco-DRR being "the sustainable management, conservation, and restoration of ecosystems to reduce risk and adapt to the consequences of climate change with the aim of achieving sustainable and resilient development" (Renaud et al., 2016, p. 4).

2.3.1 Green versus grey solutions

Although there are cases where hard, grey-engineered solutions for adaptation are necessary, there are many instances where nature-based approaches provide more cost-effective and longer-term solutions (European Commission, 2015; Rizvi et al., 2015) (although no single NbS can solve all problems (Ruangpan et al., 2020)). Many grey adaptation approaches are permanent and inflexible; this may be a key drawback in some settings (Alves et al., 2018; Jones et al., 2012). For example, grey structures have been found to significantly alter the natural adaptive capacity of flood-prone areas, making both natural and social systems, such as railways, more vulnerable to flood hazards (Bhattacharjee & Behera, 2018; Temmerman et al., 2013). Meanwhile, most natural ecosystems are inherently adaptable; for example, subject to local conditions, coastal wetlands can migrate inland as sea levels rise (Jones et al., 2012).

A further advantage of NbS is that they can often be used in conjunction with other types of interventions, complementing and enhancing the effectiveness of grey infrastructure such as sea walls and dykes in a blended, cost-effective manner (Cohen-Shacham et al., 2016; Jones et al., 2012). It is claimed that hybrid solutions, blending nature-based applications with engineered systems, may provide the optimal impact when considering environmental footprints, land requirements and cost expenditures (Fink, 2016), especially when their co-benefits are taken into consideration (Ruangpan et al., 2020; The Royal Society, 2014). In this regard, the emphasis should be on NbS complementing rather than replacing grey solutions (Eisenberg & Polcher, 2019); multiple complementary NbS measures can be applied to one scenario to provide greater cumulative and spatial responses.

Bhattercharjee et al. note that, whilst in the railway context, a well-connected and highly mobile population is likely to be in an advantageous position to better cope with flood-related hazards (2018), the presence of transport infrastructure has been found to aggravate the degree of flood damage posing threat to human safety (Pregnolato & Dawson, 2018) due to the impermeability of typical construction materials triggering surface water flooding (Pregnolato et al., 2017). Given that physical infrastructure may exacerbate damages from natural hazards, its planning must be sensitive to local ecosystem dynamics (Bhattacharjee & Behera, 2018); NbS are therefore likely to better fulfil this need than grey adaptation options.

2.3.2 NbS potential in the rail context

Evidence suggests that with appropriate design and management, transport's 'soft estate' (the land owned by transport operators that is neither road nor railway (Davies et al., 2014)) and GI have the potential to not only deliver multiple ecosystem services which could benefit biodiversity and ecological connectivity, but also increase transport infrastructure's resilience to climate change (Davies et al., 2014). For example, there is potential for vegetation in transport corridors to provide sustainable drainage to:

- Help manage surface water runoff and improve water quality;

- Improve air quality by capturing or acting as a barrier to the dispersal of pollutants produced by vehicles (Davies et al., 2014);
- Stabilise embankments; and,
- Provide resilience during heatwaves (Marteaux, 2016).

'Green track', a vegetative layer composed of turf or grasses between track beds, is in widespread use in light rail (tram) networks, found in almost all central European countries (Pfautsch & Howe, 2018). Differing track engineering and operational specifications (due to factors including weight of traffic, network accessibility, inspection and maintenance requirements (Dunn, 2019)) mean that green track is not suitable for use on traditional 'heavy' rail. This review will not cover underground or light rail systems. Learning from the implementation of green track in light rail scenarios will however be applied when considering the use of NbS on conventional rail infrastructure.

The European Climate-ADAPT partnership confirm that the most advantageous adaptation measures are those that provide synergies with other measures leading to additional benefits and that NbS could therefore be used in adaptation of the rail system in a variety of ways (although they do not elaborate on these) (PEDRR, 2010). However, at a time when railways are initiating sustainable land use programmes which aim to protect ecosystems and create habitats for plants and animals on their networks (Pietras-Couffignal et al., 2021), and include challenging 'no net loss' and 'net positive' biodiversity targets (H. M. Government, 2019), the introduction of NbS could enable railways to simultaneously address both their CCA and biodiversity objectives. Acknowledging their potential to contribute to the UN SDGs, the uptake of NbS by the rail sector could facilitate industry-wide contribution to the Life on Land and Industries, Innovation and Infrastructure goals in particular (United Nations, 2021a). This would enhance rail's reputation as a reliable and environmentally sound transport mode since the growth of rail transport, encouraging the shift from road to rail for both passengers and freight (Quinn et al., 2017), would result in a reduction in greenhouse gas emissions (however, this potential can only be realised if railways are adapted to withstand impacts associated with climate change (Climate Adapt, 2019)). Wider ecosystem cultural service benefits could be derived through NbS providing enhanced scenic value to rail travellers, improving passengers' general well-being and with increased 'active travel' uptake delivering potential health benefits (Transport for New South Wales, 2017). The natural screen provided by NbS could also present aesthetic and noise reduction benefits for those living near to railways.

Further, whilst the majority of literature presents a gloomy picture of the detrimental impacts of climate change, the European Commission showcase NbS as innovative solutions to contemporary societal challenges. With governments currently having great appetites for identifying cost-effective alternatives to grey or technological solutions, it is opportune timing for NbS to be considered as CCA options for the rail environment (European Commission, 2015).

2.4 Knowledge gaps and research aims

Given that climate change affects all parts of railways in all parts of the world (Quinn et al., 2017), it is vitally important to understand how transport infrastructure should be adapted to withstand the pressures of current climate conditions and predicted future change (Eisenack et al., 2012). Due to the long asset lives of rail infrastructure, which is expected to operate for over 50 years, it is pertinent to integrate CCA into long-term railway planning, design, and management processes (Climate Adapt, 2019).

Whilst the number of articles concerning the impacts posed by climate change on transport infrastructure and operations may have grown rapidly in recent years (Hooper & Chapman, 2012), an initial search of academic literature revealed only limited coverage of CCA in the railway industry, highlighting the need for research in this area. In 2011 Eisenack et al. found literature on adapting transport to climate change to be lacking (2012); this has more recently been confirmed to still be the case (Armstong et al., 2017; Wang et al., 2020a). This scarcity of research is aligned with the wider general acknowledgement that there is insufficient literature investigating climate threats within the rail sector (Wang et al., 2020a); where it is considered, the major focus is generally on climate change mitigation, with countries only recently starting to build capacities for adaptation (European Commission, 2015).

Wang et al. (2020a; 2020c) found climate-related studies on transport infrastructure to focus on short-term climate threats, and in transport sectors such as ports and roads but not yet in the rail sector, as confirmed elsewhere (Casello & Towns, 2017; Eisenack et al., 2012). A climate risk assessment survey of UK rail stakeholders found that only one-third of participants had implemented a climate adaptation plan and less than half of those participants who had not yet developed one acknowledged they would consider developing one in future (Wang et al., 2020a). Furthermore, Eisenack et al.'s review of observed and proposed adaptation measures in the transport sector found that, despite rail being an important mode of transportation, merely 9% of all adaptations fell into this category (2012).

Recognising that research is still at an early stage, Wang et al. claim there is "a vacuum to be bridged" in the gap between existing literature on adaptation measures for rail which is either too vague or overly detailed, and research that fails to address the factors that constrict or could promote the implementation of adaptation measures (Wang et al., 2020c). Where literature does address rail CCA, Armstrong et al. identify a gap between the acknowledgement of the need for adaptation and details of the required interventions (2017).

Whilst Wang et al. recommend that 'country-specific' evaluations of rail resilience to climate change are urgently needed (Wang et al., 2020a), it could be more pragmatic to investigate impacts on rail infrastructure on a climate basis as opposed to location. Physical rail network risks will not be evenly distributed across nations, e.g., due to geographical and climate change patterns (Pregnolato & Dawson, 2018). It is recognised that the occurrence and severity of HMH are specific to regional variation (Garmabaki et al., 2021) and that the climate challenges railways face in future are already being managed somewhere in the world today (Quinn et al., 2017). Quinn et al. therefore recommend that the rail sector draws upon international analogues, where a region may increase its preparedness for projected climate changes by learning from the existing experience of the same conditions in another region [*ibid*]. For example, the regions with both climate and railway analogues to Great Britain (GB) are France, the Netherlands, Belgium, Germany and Denmark. The GB rail industry has undertaken focused stakeholder engagement on railway networks' weather resilience and CCA activities with representatives from most of these countries railways (Sanderson et al., 2016). Engineers Canada highlight the importance of coordination across jurisdictional boundaries to advance adaptation solutions and increase the resilience of the transport sector (Palko & Lemmen, 2017).

A further (social) geographic observation is that literature concerning transport sector CCA options focus mainly on the Global North (Chausson et al., 2020; Koetse & Rietveld, 2012; Wang et al., 2020c), when it is the Global South that may be more vulnerable to climate change. The Global South is more likely to suffer from less adequate infrastructure which would be less able to accommodate adaptation measures that may need to be introduced (Koetse & Rietveld, 2012), whilst also having fewer financial resources available to fund such measures. Infrastructure networks are generally not as developed as in the Global North, meaning there is a greater emphasis on expansion (Koetse & Rietveld, 2012; OECD, 2018); this may present an opportunity as it is likely to be easier and more cost effective (subject to sufficient funds and institutional capacity) to embed climate change considerations into the planning, design and construction of new infrastructure (Koetse & Rietveld, 2012; The Royal Society, 2014) than retrofit existing assets. Given the potential relative cost-effectiveness of NbS, research into their application in the rail context may present CCA options to the Global South which are significantly more economical, thus enabling the implementation of adaptation measures that may not otherwise be possible.

The general absence of academic literature on CCA in the rail context could be explained by Great Britain's rail infrastructure owner, Network Rail, taking the decision to move from "subjective and expert review-based knowledge" of weather and climate change risks to "more detailed internal analysis" of asset failure and weather data (Network Rail, 2015, p. 11), i.e., shifting from academic to grey literature. Similarly, most of the practical adaptation proposals found by Armstrong et al. were found to be in grey literature (2017) reflecting the fact that grey literature is more accessible to, and likely to be generated by actors with a frontline role in infrastructure planning, design, construction and maintenance. With regard to NbS, there has been significant research conducted on its application to respond to the impacts of climate change in cities and urban areas (Frantzeskaki et al., 2019); however, literature on its use on railways is scarce.

Recognising the importance of the rail industry's need to adapt its infrastructure to accommodate the global rise in temperatures and HMH currently being faced as well as those expected to be experienced with a changing climate, combined with the opportunity for NbS to be considered in this arena, this research presents a state-of-the-art review on the use of NbS in the context of CCA measures in the rail industry. It identifies the current status of:

- Published literature on the use of NbS in rail as CCA measures
- Examples of NbS in use in non-rail environments which may be transferable
- Gaps in current knowledge representing key areas that merit further research.

2.5 Methodology

2.5.1 Review framework

A literature review protocol was established to respond to the question "what is the evidence base on the use of NbS being implemented as CCA measures in the railway context?". Using the "PICO" approach outlined by Pullin et al. (Collaboration for Environmental Evidence, 2018), the following population, intervention, comparator and outcome elements were used to frame the review question:

- Population – railway infrastructure, globally.
- Intervention – NbS, EbA, GI or Eco-DRR.
- Comparator – No comparator was applied given that interest lies in the state of the evidence base.
- Outcome – CCA provision.

2.5.2 Search protocol

A comprehensive literature review was conducted on articles in scientific journals using three databases: Scopus, Science Direct and Web of Science. Three categories of search terms were applied to titles, key words and abstracts: railway infrastructure, NbS and CCA. Each category has its own selection of keywords used in the search. As the concept of NbS appears under different names, items relating to Ecosystem-based Adaptation (EbA), Green Infrastructure (GI), and

Ecosystem-based Disaster Risk Reduction (Eco-DRR) were used in the identification of relevant articles in the NbS category.

The search terms for the three categories were linked using the Boolean operator "AND", while the Boolean operator "OR" was used to include the key words within each search category. A complete list of the search categories and keywords used is included in Table 2-2. See Supplementary text S1 (**Appendix A**) for the full search term sequences applied.

Searches in these scientific databases resulted in only one article. Some applicable literature might have been inadvertently eliminated from the review due to the search string adopted and/or the language of publication. However, this is a clear indication that the topic is under-researched.

A review of the sole article found in this search (Kabisch et al., 2021) revealed that the inclusion of "railway" in the abstract relates to the research being conducted on a park located on a former railway site i.e., not in an operational railway setting. This paper is therefore not relevant to the scope of this research and the outcome confirms the paucity of knowledge on this topic.

Due to the absence of relevant academic literature on this research subject, Google and Google Scholar searches were subsequently conducted using key words from Table 2-2 (the full list of exact terms used in the searches is not included in Table 2-2), and combinations of these words across two or all three categories to establish material to inform the remainder of the research objectives. As a consequence, grey literature has been included in this review, with all material being sourced via Google. Documents for detailed review were downselected based on the title and abstracts' relevance to the subject, the bibliographies of useful documents were then used to inform further review and literature searches. This process was used to identify NbS examples which may be suitable CCA options for use in the rail environment across the range of climate impacts listed in Table 2-1. Given the lack of scientific and grey literature on NbS in rail, case studies, field tests, literature review findings, and conceptual examples have been provided from non-rail contexts which may be transferable to the rail environment.

Table 2-2 Literature review search terms applied

	Search category		
	NbS	**CCA**	**Railway Infrastructure**
Key words	• nature-based solutions • nature based solutions • NbS • green infrastructure • blue green infrastructure • green blue infrastructure • ecological engineering • ecosystem-based adaptation • ecosystem based adaptation • EbA • natural infrastructure • ecosystem-based disaster risk reduction • Eco-DRR • ecosystem services • climate adaptation services	• climate change adaptation • climate adaptation	• rail • railway • rail infrastructure • railway infrastructure • railroad • railway track

2.5.3 Initial findings

Findings are presented in Table 2-3; these are recorded based on the type of literature in which the NbS examples were found. Where rail-specific examples were located, they are captured either in the 'Live rail example' column or highlighted (in red text) in the column corresponding to the literature type in which the evidence was found. As shown in Figure 2-2, this approach may help to establish the level of confidence in the validity of each proposed NbS, with a higher level of evidence inferring a more robust solution. Additionally, the more times an NbS has been found in literature (reflected by multiple references), the greater the inferred level of agreement over that NbS and subsequently higher the confidence level over its potential suitability (approach taken from Mastrandrea et al., 2011; Sudmeier-Rieux et al., 2021).

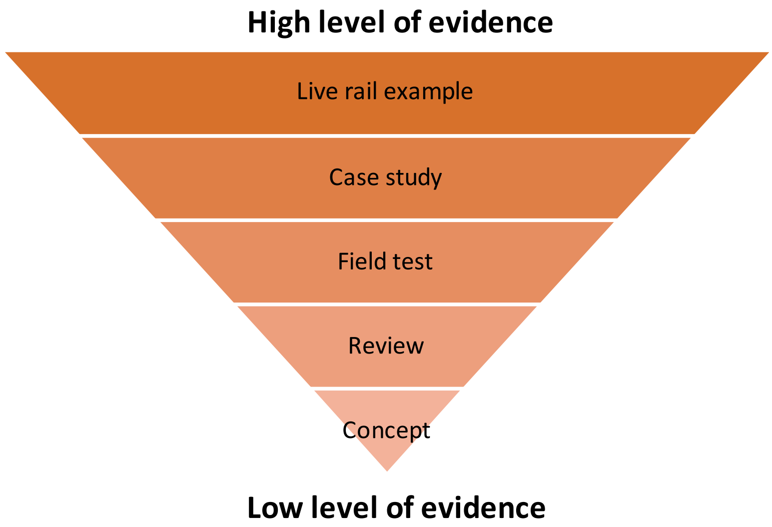

Figure 2-2 Level of evidence based on literature type used to inform potentially suitable Nature-based Solutions

2.6 Results and discussion

Five examples of the application of NbS in live rail environments were found: four in grey literature promoting best practice, and currently implemented in Australia and London, one mentioned in a journal article. The paper featuring the latter example focusses on carbon sequestration and sink, and the air pollution reduction potentials of a green railway corridor in Sydney, with Blair et al. describing the lineside vegetated and open space areas as "fine examples of green infrastructure" (2017, p. 1717). They explain how, with an appropriate selection of vegetation species, the corridors can be used to offset carbon emissions from railway operations whilst simultaneously improving air quality, reducing pollution, delivering biodiversity gains, and improving urban design and property values. Last but not least, they can ameliorate storm water flows [*ibid*]. Because the article does not explicitly mention CCA however, it did not feature in the original search results. As Sarabi et al. point out, since NbS is a relatively new concept, it is not clearly defined and thus there is a lack of understanding over what NbS are and are not (2019); this means there may be many further examples of NbS in use in rail, providing CCA services, without being recognised or labelled as such, and therefore not locatable. The launch of a Global Standard for NbS by the IUCN (2020) along with principles for their implementation and upscaling (Cohen-Shacham et al., 2019) will support increased awareness of NbS and interest in their use.

All five examples found regard NbS CCA measures in response to high precipitation, causing flooding or a resultant increased risk of erosion and landslides requiring greater geotechnical controls. This aligns with just over half of the NbS examples being found in this research concerning CCA options for high precipitation hazards (see Figure 2-3). Whilst high precipitation may not impact as many rail infrastructure assets as other HMH i.e., compared with high or low temperatures, or high winds (Figure 2-1), the frequency and/or magnitude of high precipitation events and their resultant impacts on infrastructure may have prompted a greater amount of research into NbS as CCA options for this hazard. This could also explain why the only live rail examples that were identified address this particular HMH and it is perhaps no coincidence that flood events had the largest financial impact of all weather-related events suffered in GB between 2006-2016, with costs estimated to be circa £150 million (Network Rail, 2017).

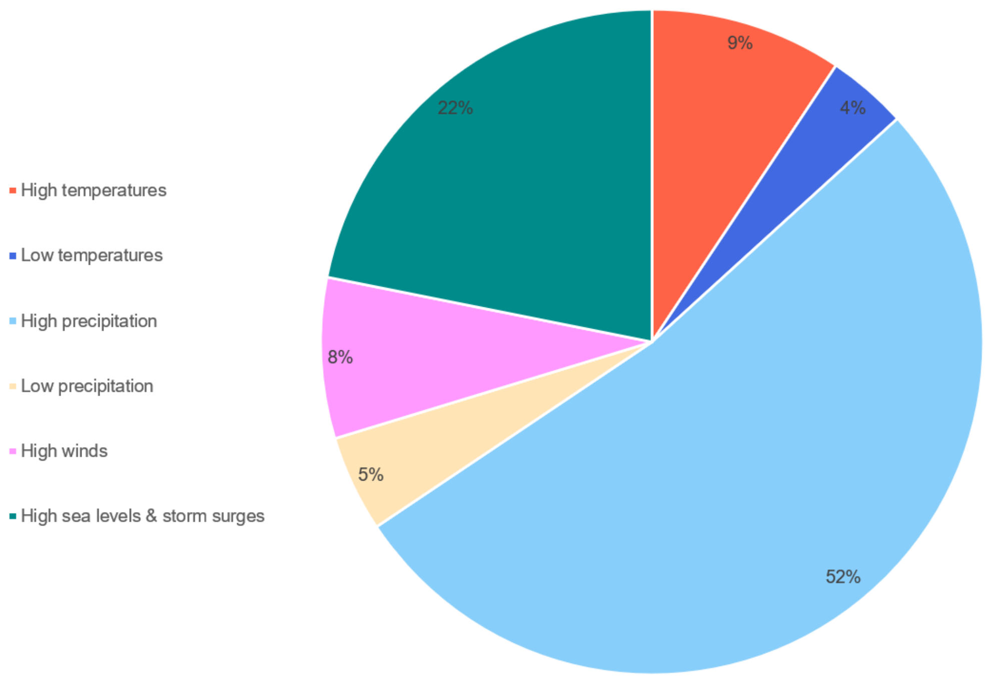

Figure 2-3 Proportion of nature-based solutions potentially suitable as climate change adaption measures for rail found in literature, per hydro-meteorological hazard

Despite not being fully examined in peer-reviewed academic literature, the five live rail examples found in this research are categorised at the top of the level of evidence hierarchy proposed in Figure 2-2 due to them currently being implemented and highlighted as industry best practice. Whilst there is a clear research gap to be addressed to prove their successful implementation, showcasing examples found directly within the rail sector strengthens the case for and provides an excellent basis on which to expand NbS research in the rail sector, providing potential case studies if/when their effectiveness has been demonstrated. The lack of scientific evidence documenting these practices – and *vice versa*, the failure for grey literature to reflect academic literature on climate change adaptation and/or the potential viability of using NbS - may reflect a lag between academic research in this area and an industrial drive to implement reactive operational responses to current extreme weather events (as before, the majority of these potentially being high precipitation events) rather than intentional, longer term climate change adaptation measures. This resonates with the findings of Lindgren et al. whose study on climate change adaptation on Swedish railways noted the implementation of non-deliberate adaptation measures in response to present day climate-related events and recommended the adoption of anticipatory, proactive and planned adaptation strategies for future climate change (2009). Climate change is extremely complex. Few railway organisations have in-house expertise on this topic, similarly, meteorologists are not railway experts (Quinn et al., 2017). Multidisciplinary collaboration between climate and environmental scientists with rail industry professionals could therefore enable the sharing of expert knowledge to support the development of CCA measures relevant to rail, including NbS.

Findings from this research have been incorporated into Table 2-1, Column D to present potential NbS options as alternatives and/or to complement grey engineered CCA options for rail infrastructure, per HMH. Figure 2-4 illustrates the NbS found to be most appropriate for each rail engineering discipline, extending Figure 2-1 to align the interrelationships between HMH, rail infrastructure (by engineering discipline) and relevant NbS. Figure 2-4 can be referred to alongside Table 2-1 to aid the consideration of NbS as rail CCA measures and may also be used to help prioritise research efforts on this topic. For example, Figure 2-1 and Figure 2-4 show that the Railway Civils and Railway Structures engineering disciplines host the infrastructure impacted by the greatest number of HMHs, suggesting that these disciplines may be priorities on which to initially focus CCA efforts. Further, as each rail discipline typically has its own suite of design, operation and maintenance standards and associated guidance, displaying the NbS relevant to each rail discipline could aid the development of targeted NbS resources, tailored to each discipline and their respective audiences.

When viewing Figure 2-4 in the context of how each category of NbS may provide CCA services to multiple rail infrastructure assets (by engineering discipline) it reveals that vegetation shading and green corridors are likely to provide CCA solutions which benefit the widest range of rail infrastructure. Further, Figure 2-4 helps to show how the use of multiple NbS at one location may simultaneously address several HMH across multiple rail infrastructure assets; this may result in a greater cumulative CCA response and the diagram may be used to inform research into finding the most effective combination(s) of NbS in this regard.

Globally, government agencies, communities and other organisations are recognising the importance of 'greening' grey infrastructure and examples of railway corridors being revegetated are beginning to appear (Blair et al., 2017). Whilst limited documented examples of the application of NbS in the rail CCA context were found in the literature review, representing an obvious opportunity for future research, both an appetite and recommendations for research on this topic were confirmed in the literature, as discussed below.

In London, UK, as part of the Thameslink Programme's Net Positive Biodiversity Policy, works on the Bermondsey Dive Under involved the construction of embankments on either side of the railway on which wildflowers were planted, creating corridors and ecological 'stepping-stones' to the wider area. A native species wildflower mix was chosen with low maintenance requirements and attractiveness to pollinators; the project described the wider NbS benefits of this feature as including reduced run-off, and an increased quality and quantity of green and blue infrastructures (Oppla, 2021a).

The Australian Adelaide – Seaford rail line provides another example of corridor greening, although much of the work involved replacing trees and shrubs which had to be removed as part of the electrification of the line. The project also aimed to create a biodiversity corridor in which flora and fauna can thrive (Blair et al., 2017); however, the study did not acknowledge (or at least document) the bonus CCA ecosystem services the vegetation would deliver.

Transport for New South Wales (TfNSW), Australia, have developed a guidance document “Integrating Green Infrastructure” which (in the only example of its kind found in research to date) promotes opportunities to integrate GI during the planning and design of transport assets, including rail corridors (Transport for New South Wales, 2017). Noting the importance of the ecological services GI provides to the public, customers, neighbours, as well as their own organisation, TfNSW declare it is “crucial” for GI to form part of planning and design thinking from the outset of a transport infrastructure project [*ibid*: p.7]. They provide guidance on how GI may be incorporated into the TfNSW network and their organisations project planning process, along with live rail examples of vegetation planting to stabilise embankments, the use of native ground cover to manage flood risk and a green wall rockfall barrier.

A further proposed example of the use of vegetation as a CCA NbS is by Network Rail in the UK who, in partnership with the Environment Agency and Leeds City Council, will be planting up to two million trees to reduce stream flow in the upper catchment of the River Aire as part of a strong focus on using “Natural Flood Management” to reduce flood risk at a location which suffers from repeated flooding (Network Rail, 2020b).

Blair et al. reference woodland planting undertaken along two and half kilometres of railway corridor and adjacent lands in London, UK (2017). The key objective of this project was aesthetic, providing enhanced views for the local community and improving the travelling experience for rail users, whilst also protecting wildlife habitats. The project failed to consider the CCA benefits this undertaking will have delivered (National Urban Forestry Unit, 2012 in Blair et al., 2017), meaning a lost opportunity in support of the body of evidence for this ecosystem service. It should be noted that linear vegetation corridors such as railways do not only have positive effects; they may also facilitate the spread of invasive species (Network Rail, 2020b; Travers et al., 2021) and attract pests (Staudinger et al., 2012).

The promisingly titled “Adaptation of Melbourne’s Metropolitan Rail Network in Response to Climate Change” study (Department of Climate Change and Energy Efficiency, 2011) considers a range of adaptation responses, including infrastructural and non-infrastructural options. Each of the infrastructure adaptation strategies focused on grey engineering solutions. The only potential inclusion of NbS is proposed in the recommendation to shade signalling equipment, although the report does not explicitly state or suggest that this will be via the provision of vegetation cover. Great Britain’s Rail Safety and Standards Board (RSSB) does recommend this use of vegetation to provide shading for lineside equipment. They also promote targeted planting of vegetation around track at risk of overheating to reduce air and surface temperatures of track, highlighting that these options may also have benefits for local drainage issues (Marteaux, 2016). In a further report, the RSSB recommend that research be conducted into options for long-term vegetation strategies to ensure the stability of earthworks and soil structure, and to reduce risks from high winds, leaf fall and flooding of all types given projected climate change; suggesting this be considered as taking a GI approach to the design and operation of the Great British railway (Rail Safety and Standards Board Ltd., 2016).

Each of the above examples confirm avenues for further research to help quantify and qualify the effectiveness of NbS as CCA measures in the rail environment. It is recognised that many factors would have to be considered to enable their implementation, and the identification of issues that may present barriers to, or support their uptake, is crucial to enabling their introduction as viable CCA options.

Table 2-3 Potential Nature-based Solutions which may be implemented as adaptation measures to impacts to railway infrastructure from impacts of hydro-meteorological hazards (red text indicates rail-specific examples)

Hydro-meteorological hazard	Live rail example	Case study	Field test	Review	Concept
High temperatures		• Use of green corridors to provide cooling (Klimatek Project 2016, 2017; UnaLab, 2019)	• Use of plants and mosses to control soil temperature supporting evaporative cooling (Williams, 2019)	• Green corridor to provide cooling (Davies et al., 2014; Sahani et al., 2019) • Vegetation selection to reduce fire risk (Lindgren et al., 2009)	• Use vegetation for shading and cooling (Climate Adapt, 2019; Metro, 2019) • Selection of suitable vegetation for near the rail corridor (Climate Adapt, 2019) • Use of plants with relatively high moisture content and low levels of volatile oils (Transport for New South Wales, 2017) • Practice the controlled removal of vegetation to prevent wildfires (European Commission, 2015; Sutherland et al., 2014)
Low temperatures	• Green walls to prevent rockfall			• Forests to stabilise snow reducing the	• Thermogenic plants

Hydro-meteorological hazard	Live rail example	Case study	Field test	Review	Concept
	(Transport for New South Wales, 2017)			risk of avalanches (PEDRR, 2010) • Vegetation management to prevent snow loaded trees and branches falling onto tracks (Rail Safety and Standards Board Ltd., 2016) • Vegetation strategies to ensure the stability of earthworks and soil structure (Rail Safety and Standards Board Ltd., 2016) • Forests to protect against rockfall (PEDRR, 2010)	
High precipitation	• Vegetation strategies to reduce risks from flooding (Blair et al., 2017; Oppla, 2021a; Transport for New South Wales, 2017)	• Wetlands construction, restoration and conservation (Bertule et al., 2014; Chausson et al., 2020; European Commission, 2015;	• Japanese Millet monoculture or dominated seed mixture for soil erosion control (Fox et al., 2011) • Forest management to reduce stream flows	• Vegetation cover and root structures to protect again soil erosion (Davies et al., 2014; PEDRR, 2010) • Ponds, wetlands, strips, hedges,	• Vegetation strategies to ensure the stability of earthworks and soil structure (Rail Safety and Standards Board Ltd., 2016) • Vegetation strategies to reduce risks from

Hydro-meteorological hazard	Live rail example	Case study	Field test	Review	Concept
	• Green infrastructure for embankment stabilisation (Transport for New South Wales, 2017)	Liquete et al., 2016; UnaLab, 2019) • Establish flood bypasses (Bertule et al., 2014) • Riparian buffers (Bertule et al., 2014; UnaLab, 2019) • Bioswales, detention ponds, infiltration basins, living fascines, planted embankment mats (UnaLab, 2019) • Reconnecting rivers to floodplains (Bertule et al., 2014) • Re/afforestation and forest conservation (Bertule et al., 2014) • Restoration of ponds and lakes, renaturing rivers and streams, Sustainable Urban Drainage Systems (Klimatek Project 2016, 2017)	(Ford et al., 2011; Kelly et al., 2016) • Use of moss and lichens for erosion control (Wei et al., 2015) • Use of nature-based erosion barriers for rangeland (Kimiti et al., 2017) • Stable enduring species as erosion control (Krautzer et al., 2011) • Use of grasses to rehabilitate Badlands, facilitating soil erosion control (Talema et al., 2019) • Parallel contour seeding as run-off control [Badia et al.in (Chausson et al., 2020) • Use of seeded perennial grasses for erosion control (Porensky et al., 2014)	shelterbelts, bunds & riparian buffer (Kumar et al., 2020; Sahani et al., 2019) • Sustainable drainage systems, bioretention swales and basins (Kumar et al., 2020; PEDRR, 2010) • Forests to reduce flood risk (PEDRR, 2010) • Peatlands and grasslands to store water (PEDRR, 2010) • Soil bioengineering, cultivation or restoration of slopes, live fascines, vegetating crib walls, optimise management of forests, rivers and streams (Kumar et al., 2020) • Biotechnical stabilisation to enhance grey	flooding (Rail Safety and Standards Board Ltd., 2016) • Use plantings for erosion control (Metro, 2019) • Use wetland and other natural infrastructure to help control flooding (Metro, 2019; Sutherland et al., 2014) • Small watercourses are better than man-made drainage (Lindgren et al., 2009) • Retain forest cover on steep slopes (European Commission, 2015; Sutherland et al., 2014) • Encourage re-vegetation of riverbanks (European Commission, 2015;

Hydro-meteorological hazard	Live rail example	Case study	Field test	Review	Concept
		• Introduction of grassland to alleviate runoff and flooding (Chausson et al., 2020; Evans & Boardman, 2003)au • Vegetation used as watershed management (Amini et al., 2014; Chausson et al., 2020) • Introduction of grassland to alleviate erosion (Evans & Boardman, 2003) • Restoration of degraded vegetation (Hao et al., 2017) • Natural revegetation as soil erosion control (Fu et al., 2011; Jiang et al., 2016; Jiang & Zhang, 2016)	• Natural revegetation (Jiao et al., 2012) • Artificial sparsely forested grassland restoration for erosion control of sandy grasslands (Yuan et al., 2012) • Retention of mature forest as soil erosion control (Zhao et al., 2009) • Avoid use of non-native herbs when revegetating (García-Palacios et al., 2010) • Natural fallow as soil erosion control (Quinn et al., 2018) • Use of shrubs and deep-rooted grass for slope stability (Rahardjo et al., 2014) • Collective tree, shrub & herb assemblages for erosion control and landslide	engineered structures (Pierson et al., 2014) • Mulch blankets, hydro-seeded grass cover and deeply rooted woody vegetation (Pierson et al., 2014)	Sutherland et al., 2014) • Use balancing ponds to contain surges and release slowly (Sutherland et al., 2014) • Plant trees, hedges and/or perennial grass strips to intercept surface run-off (Sutherland et al., 2014) • Allow for natural erosion processes rather than try to prevent them (European Commission, 2015; Sutherland et al., 2014)

Hydro-meteorological hazard	Live rail example	Case study	Field test	Review	Concept
			prevention (Yu et al., 2012)		
Low precipitation		• Restoration of ponds and lakes, renaturing rivers and streams (Klimatek Project 2016, 2017)		• Soil conservation and connectivity of the landscape (increase infiltration or reduce surface run-off) to restrict droughts (Kumar et al., 2020) • Maintain vegetation cover in dryland areas (PEDRR, 2010) • Lakes & wetlands, blue-green infrastructure (Sahani et al., 2019)	• Vegetation strategies to ensure the stability of soil structure (Rail Safety and Standards Board Ltd., 2016) • Maintain and enhance natural wetlands (Sutherland et al., 2014)
High winds			• Strip cutting of coastal forests to prevent wind damage (Suzuki et al., 2016)	• Shelterbelts (Davies et al., 2014; PEDRR, 2010) • Greenbelts, and other types of living fences to provide wind barriers (PEDRR, 2010) • Seagrass beds, coral reefs, oyster reefs, salt marshes (U. S. Army Corps of	• Planting of trees able to withstand higher winds (Climate Adapt, 2019) • Tree selection to withstand higher wind (Lindgren et al., 2009) • Vegetation strategies to reduce risks from high winds and leaf fall (Rail Safety and

Hydro-meteorological hazard	Live rail example	Case study	Field test	Review	Concept
				Engineers et al., 2013) • Use of natural coastal ecosystems to reduce wave heights (Chausson et al., 2020)	Standards Board Ltd., 2016) • Vegetation strategies to ensure the stability of earthworks and soil structure (Rail Safety and Standards Board Ltd., 2016) • Planting of evergreen trees
High sea levels and storm surges		• Dune restoration and beach regeneration, salt marsh and coastal wetland regeneration, creation of oyster reefs (Klimatek Project 2016, 2017) • Protecting/ restoring reefs (coral/oyster) (Bertule et al., 2014) • Protecting/ restoring mangroves, coastal marshes and dunes (Bertule et al., 2014) • Dune restoration and beach regeneration (Carro et al., 2018)	• Emergent plants to attenuate waves (Yiping et al., 2015) • Vegetation of dunes to reduce coastal erosion (Martinez et al., 2016; Mendoza et al., 2017) • Creation of oyster shell reefs to reduce coastal erosion (Chowdhury et al., 2019; Piazza et al., 2005) • Restoration of sand banks, beaches & dunes (Hanley et al., 2014)	• Coastal vegetation, wetlands & coral reefs (Kumar et al., 2020; PEDRR, 2010; U. S. Army Corps of Engineers et al., 2013) • Seagrass beds & saltmarshes (PEDRR, 2010; U. S. Army Corps of Engineers et al., 2013) • Mangroves (PEDRR, 2010) • Construct artificial dunes, planting on natural dunes (PEDRR, 2010; U. S.	• Dune restoration and beach regeneration (Sutherland et al., 2014) • Create, restore and/or enhance shellfish & coral reef growth (Sutherland et al., 2014) • Protecting/restoring mangroves, coastal marshes and dunes (Sutherland et al., 2014) • Create new, restore and/or protect intertidal muds, saltmarshes &

Hydro-meteorological hazard	Live rail example	Case study	Field test	Review	Concept
		• Use of marshes (Glass et al., 2018)		Army Corps of Engineers et al., 2013) • Use of natural coastal ecosystems to reduce wave heights (Chausson et al., 2020) • Seagrass beds, Coral reefs, vegetation and wetlands (PEDRR, 2010; U. S. Army Corps of Engineers et al., 2013)	mangrove communities, seagrass beds & vegetated dunes from degradation or loss (Sutherland et al., 2014) • Seagrass beds, Coral reefs, vegetation and wetlands (Sutherland et al., 2014)

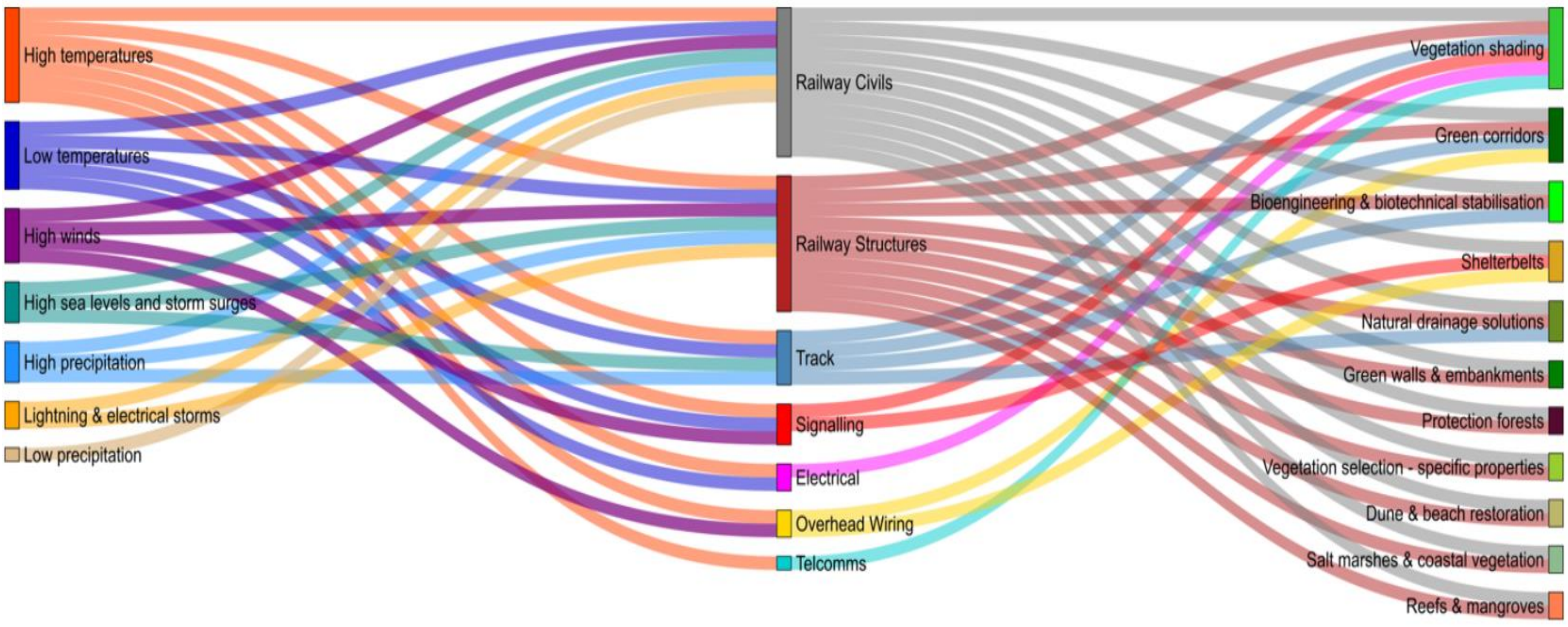

Figure 2-4 Relationships between hydro-meteorological hazards, rail infrastructure (by engineering discipline) and potentially suitable Nature-based solutions

2.7 Conclusion

Globally, the need for railways to adapt to the impacts of current HMH and future climate change is growing urgently. This research has confirmed NbS as potential candidates to be considered as CCA options for railway infrastructure, with few examples being found to be in place alongside multiple examples of NbS implemented in non-rail contexts which may be transferable to the rail industry. Whilst clear knowledge gaps have been identified on this topic, the need for long-term and cost effective CCA solutions strengthens the argument for further investigation into the suitability of applying NbS in the rail context. The consideration of rail infrastructure type, by engineering discipline, and how that infrastructure is impacted by particular HMH may help this process. Further research should include the consideration of rail industry-specific barriers to NbS implementation to enable the development of guidance to support their acceptance and uptake by the sector.

Chapter 3 Barriers and tools for implementing Nature-based Solutions for rail climate change adaptation

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Abstract:

Globally, the need for railways to adapt to the impacts of climate change is increasing rapidly. Nature-based Solutions (NbS) have been identified as potential climate change adaptation (CCA) options for rail infrastructure; however, the limited number of examples of their application on railways highlights that many factors still need to be considered to enable their wider implementation. This study identifies barriers to NbS uptake by the rail industry through a systematic literature review, categorising them into seven key themes, whilst also considering potential tools to facilitate their uptake. The ongoing development of NbS standards and guidance is confirmed as a means to resolve the barriers likely to be faced. A framework to support the uptake of NbS in the rail industry

is presented and discussed in the context of the existing literature, with climate change risk assessments being recognised as the entry point for CCA in rail infrastructure management.

Key words: Nature-based Solutions; rail infrastructure; climate change adaptation; climate change risk assessment

3.1 Climate change impacts on rail infrastructure and adaptation options

Globally, transport infrastructure are exposed to hydro-meteorological hazards (HMH) (Jaroszweski et al., 2010; Thornes, 1992) such as floods, droughts, storm surges and temperature extremes (Debele et al., 2019). As the duration, magnitude, scale, and frequency of HMH are expected to be exacerbated by future climate change (IPCC, 2021, 2022), the exposure of rail infrastructure to conditions which were not considered at the time of their design may reduce its lifetime, impact the safe operation of rail services, and increase operational and maintenance costs (Palko & Lemmen, 2017). This presents a significant challenge in managing the resilience of rail infrastructure globally to cope with and respond to current weather extremes and those anticipated under a changing climate (Blackwood et al., 2022; Davies et al., 2014).

The majority of climate change adaptation measures currently in widespread use on rail infrastructure are grey-engineered solutions, such as seawalls and increased culvert sizing (Blackwood et al., 2022). The same trend is observed globally in terms of measures put in place to adapt to the consequences of climate change. It is however increasingly recognised that nature-based (or ‘green’) solutions can complement these methods (Seddon et al., 2020a). This should also be the case for the rail industry. Nature-based Solutions (NbS) is considered as “an umbrella concept” covering a range of ecosystem-based approaches (Cohen-Shacham et al., 2016) including Ecosystem-based adaptation (EbA), Green Infrastructure (GI) and Ecosystem-based disaster risk reduction (Eco-DRR), all of which are highlighted as being particularly well suited to addressing climate change impacts on rail infrastructure (Blackwood et al., 2022). NbS are defined as “actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (Cohen-Shacham et al., 2016, p. 2). Multiple NbS measures may be combined to provide greater cumulative and spatial responses to one climate risk scenario (McVittie et al., 2018); NbS may often also be used alongside other intervention types, supplementing and augmenting the efficacy of grey infrastructure in a "blended, cost-effective manner" (Cohen-Shacham et al., 2016).

Internationally, the importance of 'greening' grey infrastructure is being recognised by government agencies, communities and other organisations, and the revegetation of railway corridors is beginning to be seen (Blair et al., 2017). Despite a rapid growth in the number of articles regarding climate change impacts on transport infrastructure and operations (Hooper & Chapman, 2012), a recent search of scientific and grey literature revealed very scant coverage of rail industry CCA (Blackwood et al., 2022). Blackwood et al. (2022) also found that, thus far, very few studies have explored the potential application of NbS as CCA measures in the rail industry. Only five examples of NbS being utilised in live rail environments were found, along with a number of case studies, field tests, literature review findings, and conceptual examples of NbS providing CCA measures in non-railway settings which may be transferable to the rail environment. Blackwood et al. (2022) also present the relationships between key HMH which can detrimentally impact rail infrastructure grouped by 'engineering discipline' (e.g., Track, Signalling), and highlight the types of NbS which may be used as potential substitutes or supplements to grey engineered rail CCA options (ibid).

Given that climate change "affects all parts of railways in all parts of the world" (Quinn et al., 2017, p. iii), there is an urgent need to develop cost-effective, long-term CCA solutions for rail infrastructure (Blackwood et al., 2022). It is becoming critically important to understand how new and existing rail infrastructure should be modified to withstand existing weather extremes, as well as conditions predicted under future climate change (Eisenack et al., 2012). It is acknowledged that many factors would have to be considered to support the widespread deployment of NbS, with the identification of issues that may present barriers to, or support the uptake of, NbS by the rail industry being crucial in facilitating their establishment as practicable CCA options. Whilst barriers to the adoption, implementation and diffusion of NbS have been identified in many different contexts in previous studies (Davis & Lafortezza, 2019; Frantzeskaki et al., 2019; Kabisch et al., 2016; Sarabi et al., 2019; Sarabi et al., 2020), these have not yet been identified in the rail industry. This review therefore identifies barriers to the uptake of NbS on rail infrastructure and presents potential solutions to overcome these, including a proposed framework to incorporate NbS as CCA options in current rail infrastructure management practices. This study contributes to two growing bodies of knowledge: (1) the practical application and upscaling of NbS, and (2) CCA options for railways, with the intention of presenting rail infrastructure owners/operators and scientists with factors to evaluate when considering the potential use of NbS as a CCA measure. This paper presents an approach to embed climate change risk assessment (CCRA) and subsequent CCA measures in rail infrastructure, whether these be NbS and/or hybrid (i.e., a combination of NbS with grey-engineered options). We do not consider railway buildings, e.g., stations or signal boxes in this research.

3.2 Methodology

3.2.1 Review framework

This study uses the literature sourced through the systematic search conducted by Blackwood et al. (2022) on the use of NbS for CCA in the rail industry. The full text of the literature was qualitatively analysed for content on the barriers, along with the potential solutions and tools to facilitate CCA planning and the operationalisation of NbS. These topics were considered from a general perspective, i.e., not solely within the rail industry, in order to gain broader knowledge of issues that may be relevant to the rail context. Rail-specific literature was reviewed to identify CCA implementation challenges pertinent to the rail industry, and to enable the application of a rail-specific lens to the wider CCA and NbS operationalisation challenges found in the non-rail literature. Given the paucity of information on NbS being used in rail (Blackwood et al., 2022), rail-specific documents were evaluated based on their consideration of the broader theme of the challenges associated with vegetation management, as the introduction of NbS to the rail environment would entail additional vegetation that would need to be managed. The scope of the review considered practical barriers that may be encountered during the lifecycle of railway infrastructure (i.e., from its planning, design and construction, its operation and maintenance, through to decommissioning), whilst also encompassing broader rail industry institutional and organisational practices which may hinder the uptake of NbS, in both urban and rural settings.

3.2.2 Search protocol

The literature review was conducted on the peer-reviewed articles in scientific journals and on grey literature collated by Blackwood et al. (2022), using the following databases and search engines: Scopus, Science Direct and Web of Science, Google Scholar and Google. Documents were selected based on the title and abstracts' relevance to the subject, and the bibliographies of useful documents were then used to direct further literature searches. The review process continued until the identified sources did not provide any new insights into potential barriers.

3.2.3 Identification of barriers to the uptake of NbS as climate change adaptation measures for railway infrastructure

Barriers to CCA planning, in the rail context and beyond, and to the general operationalisation of NbS were collated. The general challenges of managing vegetation in the rail environment were also recorded. The findings were grouped into seven common themes which emerged, as presented in Figure 3-1. The themes include both physical, practical challenges that may be encountered when seeking to implement NbS in an operational railway environment, as well the hurdles posed by more strategic rail industry policy and management conventions. Through the process of identifying barriers, several possible solutions to overcome these hurdles were discovered, with many of the solutions potentially being able to address multiple challenges, as discussed in the following sections. Due to the limited published scientific literature on the use of NbS as CCA measures for rail (as reported in Blackwood et al., 2022), the analysis of the barriers and subsequent solutions identified remained qualitative.

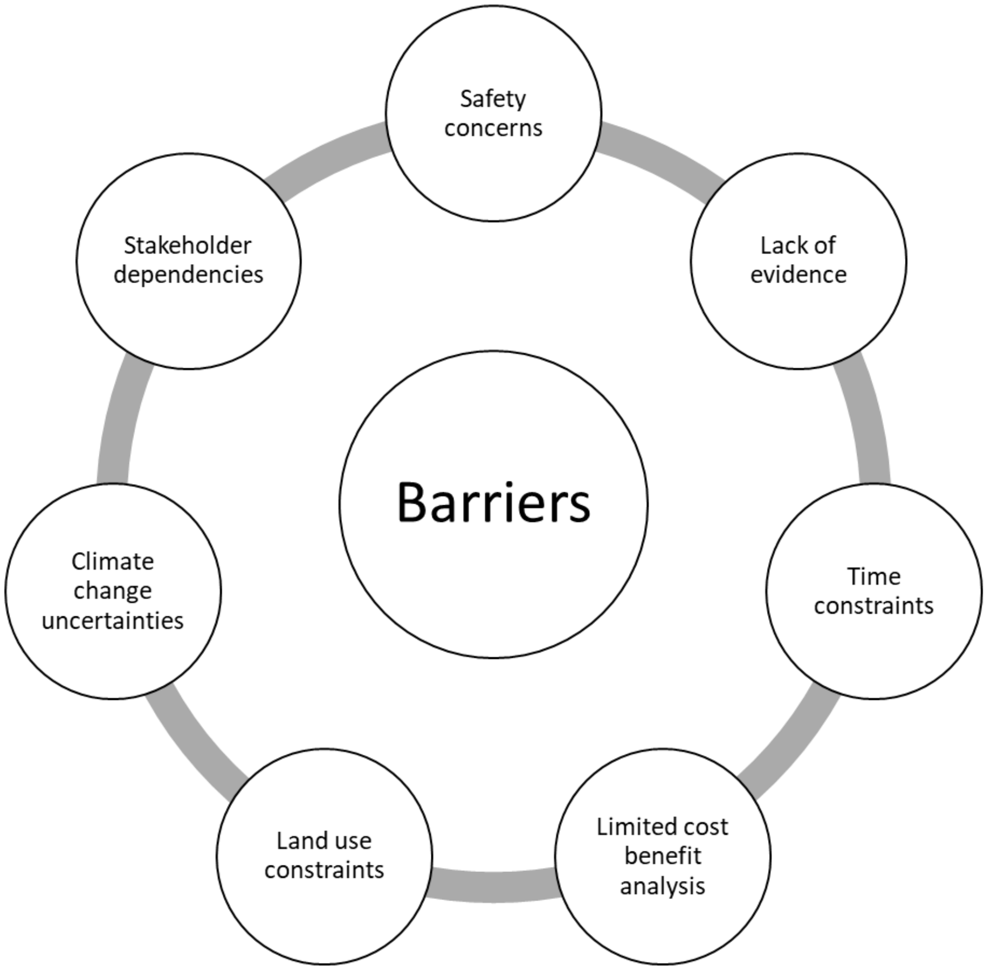

Figure 3-1 Barriers to the uptake of Nature-based Solutions as climate change adaptation measures for railway infrastructure, as emerging from the literature review

3.3 Results: identified barriers to the uptake of NbS as climate change adaptation measures for rail infrastructure

3.3.1 Safety concerns

In Great Britain (GB), Network Rail identify critical dependencies which must be maintained to enable the "safe, efficient and reliable operation of rail assets" (Network Rail, 2015, p. 18). Vegetation can pose the following safety hazards: falling onto the track, striking overhead line equipment, blocking signal sighting, blocking visibility for level crossing users, blocking safety refuges for rail workers, striking railway vehicles, obscuring assets (hindering their inspection), leaf fall affecting train braking, blocking of drainage (Network Rail, 2020a), and injurious weeds causing harm to rail workers and/or nearby receptors (Network Rail, 2020a, 2020c). The ongoing management of vegetation is therefore critical to the safe operation of the railway.

Given that many of the climate-related impacts to rail infrastructure are caused by vegetation, with trees in particular presenting hazards across several climate conditions (Blackwood et al., 2022), it is understandable that rail infrastructure owners are seeking to manage or completely remove it from rail corridors. Several of the CCA measures cited by Blackwood et al. (2022) which require the removal of vegetation from the rail environment, i.e., tree-free zones and de-vegetation programmes, therefore contradict the notion of applying NbS in the rail environment, thus presenting a significant barrier to their uptake in this specific context.

Whilst appreciating some of the benefits provided by lineside vegetation, Network Rail still claim that, in many cases, the advantages of de-vegetation are likely to exceed the value that the presence of the vegetation provides (Network Rail, 2020c). Many of their regionally-based maintenance teams are undertaking works to significantly reduce tree cover, although in many cases there is a priority to focus on "high-risk" trees in danger of falling across the running lines (Network Rail, 2020c). The European Climate-ADAPT partnership recognises that creating wider rail corridors in order to reduce the risk posed by falling trees may compromise other objectives; for example, a wider corridor, allowing greater temperature variations in the track area, does not support efforts to reduce vulnerability to fires or rail buckling (Climate Adapt, 2019).

When considering the potential use of NbS, careful plant selection will be required to ensure that size and maintenance requirements do not affect the safety of rail operations (Blair et al., 2017; Transport for New South Wales, 2017). There is also a risk that vegetation introduced to the rail network would be vulnerable to increases in maximum wind speeds experienced during storms, causing it to fall onto the tracks, which could have significant implications for the rail network (H. M. Government, 2017). Similarly, careful consideration would have to be given to the location of protection forests planted in response to increased threat of landslides in wet conditions. In Australia, whilst it is noted that an increase in vegetation, especially tree cover, would be beneficial to combat urban heat island effects and extreme heatwaves in cities (Lin et al., 2016), it is recognised that the climate benefits that can be gained through increasing vegetation cover would have to be balanced with potential "ecosystem disservices" (Shackleton et al., 2016). For example, ecosystems may present an increased bush fire hazard, or tree roots may cause damage to infrastructure (Lin et al., 2016). In areas prone to bushfire it is recommended that vegetation possessing high moisture and low volatile oil content should be selected (Transport for New South Wales, 2017). Linear vegetation corridors, such as those found alongside railways, can also exacerbate the spread of invasive species (Benedetti & Morelli, 2017; Travers et al., 2021) and the attraction of pests (Staudinger et al., 2012). Due to the presence of below-ground utilities in the railway corridor, including high voltage electrical cables, consideration must be given to the placement of NbS when planting and maintaining vegetation to avoid electrocution and other safety hazards (Transport for New South Wales, 2017). The careful choice of species, the location of, and management arrangements for vegetation are therefore essential to limit negative safety outcomes from the introduction of NbS to the rail environment. In light of these challenges, to aid the selection of suitable NbS and determine the criteria to be considered when planning their placement and ongoing maintenance requirements, the development of NbS design and maintenance standards with associated guidance would be a useful tool. Since rail engineering disciplines generally have their own suite of standards and guidance, the determination of NbS pertinent to each discipline would support the preparation of NbS resources bespoke to and targeted at each discipline.

With an anticipated increase in temperatures likely to extend the growing season, the duration of safety and performance risks caused by vegetation is expected to rise further, entailing an increase in the vegetation management activities that will be required to mitigate such risks (Network Rail, 2020d). The resulting more vigorous plant growth may cause structural problems, for example on rock slopes where “root jacking” can accelerate the deterioration of the rock face, and consequently require a more frequent maintenance regime (Network Rail, 2020e). Also, the expected shift in tree species mix whereby colder climate trees are unable to endure warmer climates and better adapted species become more dominant, could prompt a greater rate of trees dying (Network Rail, 2020e). This could lead to a greater risk of trees falling onto the track, and the subsequent lack of vegetation could cause embankment instability, contributing to the potential for landslips to occur when the bare embankment is then also exposed to extreme HMH (Hooper & Chapman, 2012). Discussing the example of measures to prevent slope failures, Kumar et al. (2020, p. 19) note that, in many instances, “a nature-based alternative may be a more sustainable and cost-effective solution” to grey options. They also note that, if public safety were to be compromised, the most robust intervention must be applied and therefore in this arena, “NbS for landslide mitigation must still prove its feasibility” (Kumar et al., 2020, p. 19). Whilst it would be desirable to learn from failures in terms of NbS implementation in general, it can be difficult to gather data on these aspects (Kabisch et al., 2016), and, given the potentially catastrophic consequences of the failure of rail infrastructure, it is essential that decisions on and responses to CCA in the rail environment are based on robust evidence (Network Rail, 2015).

Legally, company directors have a duty of care and diligence to take steps to mitigate against risks which may cause harm (Quinn et al., 2017). Climate-related risks represent foreseeable risks of harm to the travelling public, rail workers and those in, on, or near rail infrastructure. Therefore, if directors of railway organisations fail to address climate change risks now, in the future they could be found liable for breaching their duty of care and diligence (Hutley & Hartford Davis, 2019). Transport is highlighted as a sector that is required, and expected, by regulators and investors to engage on their management and responses to climate change risks (*ibid*). This does not only strengthen the case for the consideration of CCA measures for rail on safety grounds but also represents the (safety-focused) risk assessment processes currently embedded within the rail industry (e.g., An et al. (2013), Office of the National Rail Safety Regulator (2020), Rail Safety and Standards Board Ltd. (2021)) as vehicles to incorporate the management of climate change risks into the planning, design, construction and maintenance of rail infrastructure. This will support the incorporation of CCA measures into rail infrastructure, and in turn facilitate the inclusion of NbS as potential adaptation responses. National and international CCA standards and principles have been developed which include requirements and guidelines for undertaking Climate Change Risk Assessments (CCRA) e.g., Standards Australia (2013) and The British Standards Institution (2019), and transport infrastructure owners have subsequently established CCRA frameworks and supporting guidance (Network Rail, 2021b; Queensland Government, 2020; Transport for New South Wales, 2016). The roll-out and implementation of these approaches across the rail industry will support an increased consideration of the climate change risks to rail infrastructure, encouraging the inclusion of CCA measures and opening an avenue to incorporate NbS. The figures produced by Blackwood et al. (2022) which show the relationships between HMH and rail infrastructure and suggest the potential NbS concepts that could be applied to rail infrastructure assets could be used during the CCRA process to help identify the risk that HMH pose to each rail engineering discipline, whilst also aiding the selection of suitable nature-based CCA options to treat or control the impact of the risk. Climate change is, however, one of a multitude of risk factors that need to be managed in railway engineering (Lin et al., 2011), with other considerations including safety, security, cost, and operational disruption. The strategic risk management of railway infrastructure, including the selection of risk reduction measures therefore requires a balanced approach to optimise the provision of safe, reliable, resilient and affordable rail services. Standards Australia (2013, p. 22) recommend that a CCRA risk management framework should take a range of external factors into account including "social and cultural, legal, regulatory, financial, technological, economic, natural and competitive environment, whether international, national, regional or local". Applying this rationale to the overall risk management of rail infrastructure would facilitate the holistic analysis and evaluation of risks across a breadth of social, economic and environmental criteria. This approach is recommended by Martani et al. in the selection of preventive and corrective railway infrastructure interventions, which would aid the selection of sustainable solutions and therefore potentially paving the way for NbS to become a common feature (2017).

The growth of vegetation on railway track is perceived to have negative impacts on the safe operation of the railway and its infrastructural integrity. It is therefore considered essential to keep the track area 100% vegetation-free (Pietras-Couffignal et al., 2021). Research projects have commenced in Europe to investigate the impact of the presence of vegetation on railway tracks and walkways to determine quality standards for plant coverage (*ibid*). This provides an opportunity to better quantify the safety risk posed by lineside vegetation; if this is found to be lower than it has historically been perceived, it may allay concerns about vegetation, thereby potentially supporting the uptake of NbS. Further, the use of railway track materials which are impermeable to plants (e.g., concrete, slab track, asphalt) could be incorporated into designs to enable planting alongside the tracks (Pietras-Couffignal et al., 2021). When combined with NbS, these grey engineering solutions could therefore become a viable hybrid CCA option.

3.3.2 Lack of evidence

NbS have been highlighted as solutions to enhance resilience to climate change; however, the body of conceptual and practical knowledge over their use is fragmented (Sarabi et al., 2019).

As ecosystems are self-organising and their growth is based upon multiple factors and interactions, it can be difficult to predict the outcome of nature-based management interventions with certainty (Blair et al., 2017; Sarabi et al., 2019). Whilst the growth and evolution of an NbS over time at no cost to humans is presented as benefit in terms of lower capital, maintenance, and operational costs (Pakzad & Osmond, 2015), the "uncertainty" of ecosystem development (Blair et al., 2017) can present a potential deterrent to its uptake as a CCA measure. When compared to grey solutions, (Jones et al., 2012) confirm that EbA lack the quantitative adaptation capacity estimations that can be determined for built structures by applying engineering-based calculations, putting EbA and wider NbS at a disadvantage. Further evidence is therefore required to assess NbS effectiveness compared with technology-based grey solutions to help confirm the suitability of NbS and to potentially aid their selection over grey engineered alternatives (Kabisch et al., 2016). Kumar et al. (2020) confirm that many NbS research and innovation actions require further development to test and prove how NbS can be turned into bankable opportunities, scaled up or transferred to other locations. In a chicken-and-egg scenario, however, limited uptake of NbS leaves the concept unclear; limited evidence exists in terms of precedence or long-term established examples, which is a key difficulty in assessing the potential effectiveness and impact of NbS (Collier, 2021; Sarabi et al., 2019). Additionally, the variety and complexity of NbS makes a standardised methodology in their design and application, and subsequently providing a strong evidence-base, more difficult (Anderson et al., 2022; Sudmeier-Rieux et al., 2021).

With an absence of legal instruments and the currently limited dissemination of standards and guidelines (Estrella & Saalismaa, 2013; Kabisch et al., 2016), this lack of information and clarity (scarce for rail at present) is frequently cited as a major hurdle, stalling the wider uptake and acceptance of NbS, as well as any potential learning from their use (Sarabi et al., 2019). In particular, the shift from the theoretical concept of NbS to its practical application is hindered by the significant lack of NbS scientific data that can be used by policy and decision-makers (Chausson et al., 2020; Kumar et al., 2020). The recent launch of a Global Standard for NbS does however provide “a user-friendly framework for the verification, design and scaling up of NbS” (IUCN, 2020, p. 3). Developed as a facilitative standard, the framework comprises criteria and indicators intended to support users in their applying, learning and continuously strengthening and improving the effectiveness, sustainability, and adaptability of their NbS interventions (ibid). The standards, however, do not specify practical NbS options that are likely to be sought by those considering CCA solutions; this is consistent with the view that the body of knowledge regarding NbS remains largely academic (Sarabi et al., 2019). Authors therefore highlight the need for on-site experimental evidence to develop a firm evidence base and demonstrate the successful performance and cost-effectiveness of NbS (Frantzeskaki et al., 2019; Jones et al., 2012; Kumar et al., 2020). When conducted at an appropriate scale, experimentation through demonstration sites provides opportunities to evaluate the costs and benefits of “real” examples (Fink, 2016). The use of Open-Air Laboratories (OAL), which bring scientists and communities together to research environmental issues (Davies et al., 2011), is promoted as a means of providing proof-of-concept for the wider acceptance of NbS (Kumar et al., 2020). Using OAL in the rail setting to build solid evidence on the benefits of NbS under different conditions (Kumar et al., 2020) would generate an evidence base to better inform decision-making and supporting a stronger argument for NbS (Frantzeskaki et al., 2019).

Further evidence of the effectiveness of NbS in rail may be transposed from comparable situations, such as road networks (Davies et al., 2014). In their study on the application of a green infrastructure approach on transport networks, Natural England state that, whilst there are parallels between road and rail transport modes, there are key contrasts in terms of vehicle type and frequency, and the ease of accessing verges, meaning that maintenance regimes for roadside verges may not be appropriate for rail (Davies et al., 2014). They suggest an extension of their study to consider "other transport/linear corridors, such as canals and rivers, cycleways, and potentially other linear infrastructure networks such as the national grid network" (ibid). This analysis may not only benefit multiple sectors through the cross-pollination of improvement initiatives but may also generate new adaptation opportunities by applying one system to bolster the resilience of another (Wang et al., 2020c).

3.3.3 Land use constraints

Limited land space directly accessible to railway infrastructure owners represents a further barrier to the uptake of NbS which generally require more land to deliver benefits as compared to conventional grey infrastructure (Albert et al., 2019; Sarabi et al., 2019; The Royal Society, 2014). Given the confined corridors that the rail industry typically owns and operates within, the shortage of space could present a significant challenge to NbS uptake at scale in some locations without the purchase of adjacent land and/or the development of community-based solutions with neighbouring landowners, both of which are likely to be very costly and lengthy processes, for instance should the compulsory acquisition of land be required. A lack of space in which to fit NbS at a suitable scale to provide adequate CCA provision, particularly in urban zones where land is a limited and an expensive commodity, can therefore restrict the development of NbS (Sarabi et al., 2019). On this basis, variations in adaptation responses may also be required depending on whether the railway is located in an urban or a rural area; NbS options for each scenario could be reflected in the design standard/guidance suggested above. Using several NbS in one location may enable a simultaneous response to multiple HMH across various rail assets (Blackwood et al., 2022). This may provide a greater cumulative mechanism for CCA with lesser land-take required, and further research could be undertaken to find the most effective arrangement of NbS to facilitate this.

Due to the greater density and co-location of infrastructure in cities, the effects of climate change related hazards, for example floods, are amplified (Hobbie & Grimm, 2020). Whilst the resultant impacts to rail networks will disrupt a large number of people in cities (Koetse & Rietveld, 2012), urban rail passengers are likely, however, to have multiple other transit modes available to them to make their journey, whereas those in rural areas may not have other transport options, potentially leaving rail users stranded. As an example, high sea levels and storm surges caused the destruction of approximately 100 metres of sea wall at Dawlish in the UK in 2014 (see Figure 3-2); the railway line running through the Devon town is the only route linking much of the county and all of neighbouring Cornwall to the rest of the GB network (Network Rail, 2019a). This event cut off rail services to and from the Southwest peninsula for approximately two months, with estimated economic losses of £1.2 billion (Quinn et al., 2017).

Figure 3-2 Collapse of Dawlish sea wall in February 2014
(Network Rail, 2019a), reprinted with permission.

Whilst fenced railway corridors may present secure environments for biodiversity to thrive (Blair et al., 2017) by maintaining “green corridors” which connect habitats and increase the similarity of species between separated sites, such corridors may detrimentally affect the composition of species and variety of plant communities (Travers et al., 2021). The use of NbS on railway corridors could therefore potentially create barriers to species dispersal, habitat loss and fragmentation and expedite the spread of plant diseases, invasive species, and insect infestations (The World Bank, 2008; Travers et al., 2021). “Semi-open corridors” are recommended as alternatives to conventional corridors and these may help prevent such potential issues (Eggers et al. 2010, in Travers et al. (2021)). Consisting of a mosaic of habitats, semi-open corridors provide species-rich, high structural diversity solutions at a landscape level (Travers et al., 2021), i.e., beyond the railway corridor. The land-take needed is likely to require significant consultation and negotiations with third parties (including stakeholders from other industry sectors, as discussed above) which in itself may present significant challenges due to the multiple landowners that may be involved and restrictions in land availability (McVittie et al., 2018). The co-development of NbS options spanning rail and non-rail owned land may also provide mutual benefits for both parties, with this approach supporting the NbS principle (Cohen-Shacham et al., 2016) and Global Standard criterion (IUCN, 2020) to apply NbS at a landscape scale. The latter (Criterion 2, IUCN, 2020) encourages the design of NbS to be informed not only by the geographic scale, but also economic and societal scales, to facilitate the development of solutions that recognise and address interactions between these three dimensions, both at and beyond the extent of the immediate intervention site. The inclusion of such guidance in rail-specific NbS planning and design standards would promote the management of the social, economic and ecosystem risks presented by climate change beyond the confines of railway infrastructure. This could strengthen the argument for working with neighbouring landowners to develop larger scale, complementary solutions which maximise CCA benefits at a landscape scale.

Some railways have launched sustainable land use agendas which include ambitious "no net loss" and "net positive" biodiversity targets (H. M. Government, 2019) and therefore, due to the limited space (and the above-mentioned safety constraints) for planting vegetation within the confines of the narrow railway corridor, working with third parties to offset revegetation on non-railway land would enable mutualistic CCA measures, allowing the rail industry to tackle their objectives for both CCA and biodiversity simultaneously (Blackwood et al., 2022). Further, the rail industry's uptake of NbS could facilitate sector-wide contribution to the United Nations 2030 Sustainable Development Goals (United Nations, 2021a), particularly those around "Life on Land" and "Industries, Innovation and Infrastructure" (United Nations Global Compact, 2019).

3.3.4 Stakeholder dependencies

Stakeholder engagement is vital to the successful implementation of NbS projects (Sahani et al., 2019); as discussed below, engagement will be required with both external and internal parties.

3.3.4.1 External stakeholders

A significant quantity of weather-related impacts on railways are because of, or influenced by, third parties. Many of the trees that fall on the tracks are from adjacent land (Network Rail, 2015) and railway drainage systems often collect water from, and/or discharge to third-party surface water drainage systems, e.g., highways drainage (Quinn et al., 2017). Railways are therefore “heavily dependent on the use, condition, and capacity of outside party” infrastructure (Network Rail, 2020c, p. 30). Such external risks can be challenging to control due to a lack of information on third-party infrastructure, including difficulties in establishing their ownership, and the hurdles that can be encountered when trying to obtain access to land (Network Rail, 2015). Further complications can arise from interdependencies and potential conflicts with other industries and their operations; for example, power and water infrastructure (Network Rail, 2020c). Given that transportation networks depend on other infrastructure and utilities, such as electricity and telecommunications, if one sector is at risk, then so are others (Climate Adapt, 2019; Lindgren et al., 2009; Palko & Lemmen, 2017). As recommended above, climate change impacts on rail infrastructure and the subsequent identification of appropriate adaptation responses should therefore also take account of intermodal and cross-sectoral relationships; such considerations are important to avoid maladaptation (United Nations Economic Commission for, 2020). Moreover, many disruptive weather events can affect everyone in a region; working together to respond to these events (Quinn et al., 2017) may present an opportunity to those in wider industries, including parties representing different transport modes (Quinn et al., 2018), to collaborate in developing mutually beneficial CCA solutions.

Drainage poses a particular problem as the interconnectivity of drainage networks means that CCA efforts carried out on one part of the system may lead to flood risk for other connected parties, including downstream land and properties (Network Rail, 2020c). Rail’s vulnerability to flooding will therefore depend on adaption actions taken by (or with) external parties. Rail infrastructure owners may also suffer from land use change or poor land management by adjacent third parties and this may impact the effectiveness of NbS. The spread of invasive species or increased water abstraction impacting local water availability, for example, will affect vegetation growth on and near railway land. Ongoing consultation and collaboration with external stakeholders are therefore important in order to maintain the present-day functionality of railway drainage and to coordinate future improvements and upgrades (Network Rail, 2020c). The IUCN advocate that for a NbS intervention to be durable and sustainable, its design should incorporate the identification and management of risks beyond the extent of the intervention site (IUCN, 2020). Further, Cohen-Shacham et al. recommend the consideration of "upstream and downstream relationships, dependencies, and benefits" when implementing NbS interventions; these factors could therefore be included within the scope of rail infrastructure CCRA and associated consultation processes (2016, p. 30). In GB, Network Rail have identified that greater engagement must occur with external bodies such as environmental regulators, flood authorities, drainage boards and third-party landowners to make meaningful, aligned weather resilience and climate adaptation improvements (Network Rail, 2020d). Consultation with these stakeholders would support the implementation of the semi-open corridor approach introduced in Chapter 3.3.3, enabling the development of landscape scale solutions that benefit multiple parties.

CCA practitioners have identified challenges in effectively communicating the severity of climate change to the public, a particular issue being how to best communicate the need to modify infrastructure, especially given that public engagement on adaptation tends to yield conversations about climate mitigation (Palko & Lemmen, 2017). Casello & Towns (2017) state the need to emphasise the importance of both mitigation and adaptation in tandem with maximising social value from infrastructure investments. As rail has an excellent reputation as an environmentally friendly transport mode (Quinn et al., 2017), dialogue on its climate change mitigating benefits could be extended to include the adaptation measures required to enable the further greenhouse gas reducing shift from road to rail, in order to harness the public support and investment needed to fund CCA. Since NbS are a relatively new concept, their acceptance will require ongoing discourse; people are more likely to accept this solution once they have observed and understood for themselves the direct and indirect benefits NbS may provide (Sahani et al., 2019). Promotion of the wider ecosystem cultural service benefits of NbS (Millennium Ecosystem Assessment, 2005), such as the enhanced scenic value for rail travellers and provision of a natural screen with accompanying aesthetic and noise reduction benefits for residents neighbouring the railway, could also help build public support for their uptake.

The use of collaborative research and coproduction involving partnerships between researchers, practitioners, and the community is promoted as a means of advancing the planning and knowledge agenda for NbS (Frantzeskaki et al., 2019). OALs, which include the semi-open corridor approach, shared between rail and non-rail landowners and stakeholders could therefore be used to help support the wider public acceptance of NbS (Kumar et al., 2020).

3.3.4.2 Internal stakeholders

As well as the challenges associated with dealing with external stakeholders, rail infrastructure owners may also face issues in managing internal stakeholders. With complex interconnected networks and services, the rail industry involves many layers of decision-making (Doll et al., 2013). National rail infrastructure companies generally share responsibility for the design, maintenance and operation of rail networks and services with public and private carriers, with further contracts often in place between federal and local governments (Doll et al., 2013). The division of responsibilities may lead to confusion over who owns and who should maintain the NbS over their lifetime (Sarabi et al., 2019). The rail industry’s complex setting of institutions and interactions would make the application of an all-encompassing global strategy to adapt to the potential effects of climate change “challenging, if not impossible” (Doll et al., 2013, p. 7).

A further internal hurdle to the uptake of NbS is the “path dependency” of organisational decision-making which limits decision-makers to their active memory based on past experiences, often causing a resistance to change (Davies & Lafortezza, 2019). Grey infrastructural measures are firmly established in some settings and influence institutional protocols (Seddon et al., 2020b), and are present in all types of transport infrastructure (Driscoll, 2014). This means that for as long as transport planners maintain a like-for-like approach to designing, building, and maintaining rail infrastructure, it is expected that path dependencies will prevail (*ibid*). Resistance to change may be a particular barrier within the rail industry, which is steeped in grey engineering traditions, meaning that past decisions set a precedent for those made in future, restricting the prospect for “radically different physical, socio-economic, technical or institutional arrangements” (Driscoll, 2014, p. 322). Given that the introduction of NbS will embrace each of these arrangements, changing stakeholders’ attitudes (both internal and external to the rail industry) toward NbS is therefore likely to be a challenging process; breaking the path dependence will require changing the behaviours of individuals, organisations and society in general (Frantzeskaki et al., 2019), which may prove extremely difficult, internally within any one rail organisation, but would be further amplified at a country or rail industry level when considering the complex interrelationships described above.

Although some adaptation measures are relatively straightforward to implement from a technical basis, the organisational complexities that their usage brings about are considerably more problematic (De Bruin et al., 2009). It is therefore claimed that, until path dependence is broken, the full acceptance and adoption of NbS will not occur (Davies & Lafortezza, 2019). The effective amalgamation of NbS and grey infrastructure, or ‘green-grey’ integration (also known as hybrid solutions), may help in breaking path dependence towards grey infrastructure (Davies & Lafortezza, 2019; Sarabi et al., 2019), presenting a “societal steppingstone” from grey to green (Anderson et al., 2022, p. 12). This more gradual phasing in of NbS, whilst maintaining an element of grey infrastructure, is more likely to be within the comfort zone of long-standing rail engineers, and external stakeholders, with the added benefit that hybrid solutions may provide an optimised CCA solution when weighing up factors including land-take requirements and cost (Fink, 2016), particularly when taking their co-benefits into account (Ruangpan et al., 2020; The Royal Society, 2014). Such options could be included in the recommended NbS design standard and associated guidance, noting that the Transportation Research Board advocates, for the purposes of overcoming likely reluctance to change within the transport industry, the development of new standards which address climate change will require leadership by the scientific community and professional associations (National Research Council, 2008).

In addressing the challenges to the application of Sustainable Urban Drainage Solutions (SUDS), the need to disseminate information to highlight their proven ability in a format directed at key stakeholders and decision-makers is highly recommended (Castro-Fresno et al., 2013; Perales-Momparler et al., 2017). Involving rail industry stakeholders in joint OALs, which help to build a robust evidence base by demonstrating the effectiveness and sustainability outcomes of applying NbS compared to other CCA measures (Seddon et al., 2020b), could help to overcome path dependency for NbS. Collaborative OALs could aid the provision of evidence in response to questions or challenges raised regarding performance uncertainty, an approach which has been found to help appease reluctance and cynicism in selecting green solutions over traditional alternatives (Kabisch et al., 2016).

3.3.4.3 Education and awareness

Climate change is a complex subject. Very few rail organisations employ in-house specialists to deal with this topic, and likewise, meteorologists and climatologists lack railway expertise (Quinn et al., 2017). Stakeholder education and awareness are therefore key to the successful roll-out of NbS as CCA measures for rail.

The multi-disciplinary nature of CCA, combined with varied levels of awareness on the subject, may lead to confusion over where responsibilities for CCA lie, and failure to involve all relevant parties within an organisation (and beyond) in CCA planning may lead to oversights and incorrect assumptions that may affect the successful selection and implementation of the most suitable adaptation solutions. As an example, Network Rail's "Weather Resilience and Climate Change Adaptation Plan" for Scotland does not consider works to decarbonise the railway, nor local biodiversity and sustainable land use policies which are "covered under separate documentation" (Network Rail, 2019b, p. 12). This represents a lost opportunity for the consideration and development of NbS that could provide holistic solutions across these discipline areas. Furthermore, NbS are typically promoted by ecologists and biologists who speak in a "different language" to the key decision-makers (Denjean et al., 2017, p. 29; European Commission, 2018; Ruangpan et al., 2020). Decision-makers in rail infrastructure management, typically engineers and finance officers, will expect hard data that the NbS proponents may neglect due to their own research interests and bias (Denjean et al., 2017). The failure to present data in formats that can be easily understood by those who would implement NbS at the larger scale (e.g., engineering and financial data formats) could limit the feasibility of their inclusion in management approaches (ibid). This stresses the need for a multi-disciplinary approach. For example, Zhang & Chui (2019) and Transport for New South Wales (2017) highlight the variety of roles who should be involved in the deployment of GI in urban infrastructure, including civil engineers and hydrologists to design GI practices and stormwater management, urban planners to maximise their effectiveness within the wider urban environment, and biologists and ecologists to blend the hydrological and bioecological benefits of GI practices (ibid). Additionally, partnerships between railway and national and international meteorological organisations would enable the effective two-way sharing of expert knowledge to aid the evolution of CCA measures for rail.

The European Commission (EC) is developing a best-practice library to share knowledge and experience on the practical application of NbS, including potential obstacles and solutions to overcome these. There are many case studies available in various online resources, for example Faivre et al. (2017) note multiple NbS-related resources such as European Centre for Nature Conservation, 2017; GrowGreen, 2017; NAIAD, 2021; Nature4Cities, 2017; Naturvation, 2021; OPERAs Project, 2012; Oppla, 2021b; UnaLab, 2021; University of Copenhagen, 2017; Urban GreenUP, 2021. This material tends to focus on urban environments often at the street and building scale however, they do not include the railway environment. Additionally, although pilot and case study examples can provide very specific information and insights in the local context, derived from participating in the projects, direct application of the outcomes by others is not always easy. Reasons for this include (European Commission, 2018):

- The use of overly scientific language in reports;
- Specific data sets are used which are not available in every country, region or community;
- A missing step towards practical application and offering only part of the solution;
- Use of models which are not available outside of a specific research institute; and,
- Uncertainty about quality of project results.

When considering the sharing of information on and promotion of NbS and CCA, the means of communication should be an important factor. Most practical CCA proposals are found in grey literature (Armstrong et al., 2017) as such material is likely to be more accessible to those directly involved in the planning, design, construction, and maintenance of rail infrastructure (Blackwood et al., 2022). This again strengthens the case for creating a rail-specific NbS design standard with associated guidance, using a multi-disciplinary approach to tailor and target material to the HMH and NbS relevant to each railway engineering discipline. To maximise the successful interpretation and application of this material, the five problem areas identified by the EC, as listed above, should be addressed.

3.3.5 Climate change uncertainties

There has been a recent rapid increase in the number of articles regarding climate change impacts on transport infrastructure and operations (Hooper & Chapman, 2012). There is, however, a lack of studies examining climate threats within the rail sector (Blackwood et al., 2022; Wang et al., 2020c). Data on the risks to rail infrastructure from climate change may therefore not be readily available or directly useable to inform CCA decisions in the sector (OECD, 2018). This paucity of information and subsequent uncertainty on climate change impacts on rail infrastructure may therefore stall or prevent any form of adaptation measures being adopted on rail infrastructure.

One single aspect of climate change is unlikely to have a single effect on railway infrastructure (Blackwood et al., 2022). Comprehensive understanding will therefore be required of the combination of aspects that can impact infrastructure to enable adaptation strategies to be developed (Hooper & Chapman, 2012). Referring to the relationships between HMH and rail infrastructure (see Blackwood et al., 2022) and the CCRA process outlined in Chapter 3.3.1 will support the consideration of such aspects.

Whilst grey infrastructure might be ill adapted to future climates due to inaccurate projections of future conditions (Jones et al., 2012), the unpredictable impacts of climate change on ecosystem functionality may present NbS as an unattractive adaptation option. Ecosystems may suffer from direct climate impacts, for example higher temperatures and droughts, or indirectly due to management responses to the new conditions faced, such as changes in discharges in regulated rivers (Lavorel et al., 2015). Specific threats to ecosystems include the spread of invasive non-native plant species, habitat degradation, the decline of native species which are maladapted to increased temperatures and drought, and water shortages. Such threats may result in the loss of biodiversity or the reduced functionality of ecosystems and the services they deliver (Kabisch et al., 2016). OAL could be used to test NbS and confirm those that are resilient to such pressures.

As many changes to ecosystems and the regulating services they provide will emerge in the future, an “adaptive management approach” (Cowling et al., 2008, p. 3) is recommended to identify and manage the NbS selected for future use. With ecosystem degradation and destruction continuing at an accelerated rate globally, large areas of natural infrastructure are being removed before its regulating functions can be realised (Butchart et al., 2010). Uncertainty over the capacity of ecosystems to continue providing regulating services in the long run may make them a too risky option for some stakeholders, especially when compared to traditional grey alternatives which are more likely to be regarded as ‘tried and tested’. Efforts to quantify the extent of climate-induced change that ecosystems can tolerate whilst still providing regulating services will help better inform rail infrastructure managers on the feasibility of applying EbA options (Jones et al., 2012). Use of the CCRA process and outputs from OALs could support these efforts. The EC suggest mapping species’ responses to climate stresses (European Commission, 2015) as a useful tool in this regard, while Sanderson et al. (2016, p. 2) recommend the use of “climate analogues and railway analogues”, whereby a region can learn from the management of climatic conditions being confronted in another region to support its preparedness to deal with future projected changes (Quinn et al., 2017).

3.3.6 Time constraints

Time limitations are an additional barrier to NbS uptake (Sarabi et al., 2019), with the penchant for “fast solutions” reducing the attractiveness of NbS compared to grey measures, which are generally employable more quickly (Albert et al., 2019; Kumar et al., 2020). It has not yet been established which NbS interventions would perform better in the long term versus those which would deliver immediate solutions, and research will be required to confirm both the short- and long-term benefits NbS can deliver (Kabisch et al., 2016; Kumar et al., 2020). In most instances, the full advantages of NbS may only be realised in the long term (Bertule et al., 2014; Sarabi et al., 2019; Seddon et al., 2020b; The Royal Society, 2014); for example, the long growing time of protection forests is cited as a key challenge to their use for railway infrastructure in Alpine regions (Lindgren et al., 2009). Additionally, many NbS rely on plant growth cycles which can be subject to seasonal fluctuations over time (Shah et al., 2020). The successful implementation of NbS is also said to require long-term collaborative efforts by multiple stakeholders (Albert et al., 2019); this may be difficult to achieve within the “complex and changing multi-agency” (Quinn et al., 2018, p. 4) transport environment, however, where actions will be required by a range of stakeholders whose short- and long-term objectives may not be aligned (OECD, 2018).

CCA planning must also encompass long-term changes to the incidence and/or scale of extreme weather events (Jaroszweski et al., 2010). Since NbS are governed by complex natural processes that can be affected by these variables, predictions of their efficiency over longer periods of time are subject to inherent variability (Bertule et al., 2014) which again will take further research, and therefore more time, to establish. Transport networks are also complex and interlinked; they experience changes in ownership, operation and usage, and are comprised of assets with a range of ages and life expectancies (Quinn et al., 2017). Rail organisations typically have short planning horizons of five years (National Research Council, 2008) whilst railway assets often have service lives of several decades (Quinn et al., 2018). Thus, many transport planners perceive that the impacts of climate change will be experienced well beyond the timeframes of their longest plans, not realising that climate changes are already occurring and that decisions made today will affect how well the infrastructure accommodates these and future changes (National Research Council, 2008). Adaptation for rail infrastructure will therefore need to address both existing and new (proposed) assets, with relevant adaptation tools being available to manage present-day and future risks (Doll et al., 2013; Fisk et al., 2019) and incorporating means to evaluate their effectiveness and phasing over time (Quinn et al., 2018). This will also help to avoid unreliable infrastructure or expensive retrofitting (Quinn et al., 2018).

Because rail infrastructure can have a lifecycle of multiple decades, the implementation of adaptation measures should be incorporated into long-term rail management strategies (Climate Adapt, 2019). A potential approach is the "Adaptation Pathways" concept which places decision-making during CCA planning to allow flexibility and accommodate uncertainty. This approach recognises that not all climate change risks are best treated immediately and contributes information regarding the priority and phasing of adaptation actions (CSIRO, 2021). Adaptation pathways also help to prevent delays in decision-making due to "deep-uncertainty", i.e., being unable to make future decisions about an uncertain future (Quinn et al., 2018). The CCRA process could be used to prompt consideration of the timeframes involved when identifying the most appropriate CCA responses to climate risks, and the risk assessment process should include stakeholders with responsibilities covering all stages of the rail infrastructure lifecycle. A further time-related barrier is the potential for maladaptation to occur, whereby adaptation efforts that may provide short-term benefits result in problems in the longer term (Rizvi et al., 2015). Such impacts may also be revealed through OAL findings and be accounted for during the CCRA process when considering the effectiveness, and any consequences, of adaptation options.

3.3.7 Cost Benefit Analysis

At present, CCA decision-making is heavily dependent on economic assessment models customised to traditional, engineered interventions (Chausson et al., 2020) which can generally be applied with relative certainty regarding the type and timescale over which benefits will be realised (Seddon et al., 2020b). Whilst an abundance of historical cost and benefit data exists for grey infrastructure (Bertule et al., 2014), data specific to adaptation measures in transport is extremely poor (Doll et al., 2013). Furthermore, with economic analysis still at an early stage, NbS suffer from a lack of historical cost and benefit data to draw from (Bertule et al., 2014; Rizvi et al., 2015), especially so within rail. Meanwhile, the costs and benefits of NbS are often distributed across different areas and actors, whilst customary economic appraisals are generally confined to a distinct location, timeframe, or party (Reddy et al., 2015). It is therefore difficult to record and synthesise the financial advantages of NbS compared to alternatives (Chausson et al., 2020). This combination further increases uncertainty of the cost benefits of using NbS in rail, meaning that they may have to pass a higher threshold to be considered (Bertule et al., 2014). Additionally, due to the employment of conservative assumptions and current limitations in the evaluation of ecosystem services, especially those with intangible values which are difficult to monetise or that are realised many years into the future, this may result in an underestimation of the value of NbS when using traditional cost benefit analysis to compare them with other adaptation options (Bertule et al., 2014; Jones et al., 2012).

A key advantage of NbS is that, by definition, they should appreciate in value over time, unlike most grey solutions which tend to depreciate and often require upgrading (Collier, 2021). The selection of cheap construction materials may compromise the effectiveness and integrity of engineered structures (Pierson et al., 2014); however, this same rationale would also apply to the quality of vegetation chosen for use as NbS. Whilst vegetation enhancement programmes entail capital and maintenance costs, these provide wider economic benefits. Financial returns may be obtained through the vegetations' multiple ecosystem services, including some of inherent value to rail operations, such as the reduction of storm water flows and corridor-cooling effects (Blair et al., 2017). As already highlighted, NbS may also present ecosystem disservices, which means that the benefits gained through NbS usage need to be balanced against potential economic, health and cultural detriments in order to establish a complete picture of the value that ecosystems will deliver (Shackleton et al., 2016). These disservices will often be lesser than those associated with many grey interventions (Jones et al., 2012).

Difficulties may also be encountered in trying to explain the relevance of climate change to the infrastructure owners who will fund the necessary adaptation measures (grey or green); for instance, sea-level rise is a long-term process that does not fit neatly into conventional business cycles (Palko & Lemmen, 2017). A challenge therefore exists in balancing short-term expenditure with long-term benefits (Network Rail, 2015). Nevertheless, a need exists to generate a fuller understanding of the cost-efficiency of NbS compared to other, more traditional (grey) measures (Jones et al., 2012; Kabisch et al., 2016; Secretariat of the Convention on Biological Diversity, 2009). A more holistic, multi-criteria comparison should involve multi-discipline stakeholders, using scientifically proven methods and tools (Kumar et al., 2020) to apply a whole-life cycle approach to costing the multiple social, economic, and environmental co-benefits that can be derived (Chausson et al., 2020; Frantzeskaki et al., 2019; Kabisch et al., 2016; Ruangpan et al., 2020; Seddon et al., 2020b). The Australian Standard for infrastructure CCA provides a template for comparing adaptation options against a range of 'Economic efficiency' criteria, although the guidelines acknowledge that it may not be possible to quantify in financial terms the benefits and disadvantages of all adaptation options (Standards Australia, 2013). This supports the recommendation for further research on frameworks and mechanisms that harness the valuation of nature to promote "an equitable and inclusive policy" for NbS (Pascual et al., 2017 in Chausson et al. (2020, p. 17)). Without adequate financial provision, however, NbS will not be implemented. Therefore, new research to identify funding sources and incentivise the implementation of NbS is recommended (Seddon et al., 2020b).

Sustainability rating tools, such as CEEQUAL (Building Research Establishment, 2021) and the Infrastructure Sustainability Council's (ISC) Rating Scheme (Infrastructure Sustainability Council, 2021a), are increasingly being used to contractualise and incentivise the improved sustainability performance of infrastructure, including railways. The proponents of projects to build new or enhance existing rail infrastructure may mandate the achievement of specific performance levels using rating tools which award points for meeting the criteria of multiple environmental, social, economic and governance criteria (Kiwi Rail, 2021; Thameslink Programme, 2021; Transport for New South Wales, 2021). For example, under their Urban and Landscape Design criteria, the ISC reward projects which preserve and enhance "scenic, aesthetic, cultural, community and environmental resources and values" (Infrastructure Sustainability Council, 2021a, p. 36), and Urban and Landscape Design Plans that consider green infrastructure integration, biodiversity and habitat connectivity, thereby directly promoting and encouraging the use of NbS in infrastructure. Further, their Economic Options Assessment and Significant Decisions requirements state that sustainability criteria and whole-of-life considerations must be incorporated into decision-making processes, and that formal multi-criteria options assessments that consider material environmental, social and economic impacts must be completed. Specifically, options should consider "new engineering solutions, better use of or improvement to existing assets, green infrastructure" (Infrastructure Sustainability Council, 2021a, p. 133). This again demonstrates how sustainability rating tools can be used to encourage and reward the use of NbS through the application of whole-of-life, multi-criteria assessments.

3.3.8 Summary of potential aids to NbS uptake in rail infrastructure

Figure 3-3 collates the potential approaches and actions to address the challenges to NbS uptake as found in the literature and discussed in the preceding sections, presenting measures that may aid the uptake of NbS as CCA options for rail infrastructure, noting that some may address multiple barriers. It is recognised that these interventions would require development at, and subsequent governance and advocacy from, the strategic rail industry policy level to enable and support their implementation at the operational rail infrastructure management scale.

The development of railway bespoke NbS standards and guidance is confirmed as a common vehicle to resolve each of the barriers likely to be faced. Using the Global Standard for NbS (IUCN, 2020) as a starting point, this material would help address specific problems identified in the literature:

- Whilst the International Union of Railways has developed the "Rail Adapt Framework" to enable rail organisations to make progress in adaptation and improve their preparedness for climate change, the report and its accompanying guidance do not prescribe specific, practical CCA measures (Quinn et al., 2017; Quinn et al., 2018);
- There is "a vacuum yet to be bridged" (Wang et al., 2020a, p.12) in the available literature on adaptation measures for rail which is either "too vague or overly detailed" (Blackwood et al., 2022, p. 6); and,
- Whilst some literature acknowledges the need for rail CCA there are no details of the interventions required (Armstrong et al., 2017).

3.4 A framework to support the implementation of NbS as CCA options for rail

CCA is most effective when it is integrated into an organisation's existing policies, plans and procedures (Standards Australia, 2013; The British Standards Institution, 2019). The project network diagram presented in Figure 3-4 illustrates a four-stage framework that may be used to introduce NbS as options for use as CCA measures on railway infrastructure; it establishes the intervention points in current rail infrastructure management practices e.g., California High-Speed Rail Authority (2021), Government of South Australia (2020) Network Rail (2017), Wordsworth (2019), at which CCA options may be considered during projects to design and construct new rail infrastructure, or to renew or enhance existing assets. The mapping out of this process therefore also helps to ascertain where NbS can be promoted as valid alternatives or complements to grey-engineered CCA measures in existing rail project management processes.

The NbS implementation "approaches and actions" collated in Figure 3-3 have been incorporated at relevant points in the framework to support the delivery of its interlinked processes and proactively counter the various challenges that may be faced when seeking to operationalise NbS as CCA measures for rail, as identified in Chapter 3.3. The approaches and actions, numbered 1-9 in Figure 3-4, are labelled as per Table 3-1, which describes the role each serves in supporting the framework; as noted above, strategic rail industry directive and advocacy would be required to support the implementation of these measures in day-to-day rail infrastructure management practices. The numerical order of approaches and actions is based upon their grouping in Figure 3-3 where items have been collated to ease the illustration of concepts that may counter multiple barriers; the numbering does not represent any ranking of approaches and/or actions, nor the sequential order of application in later figures.

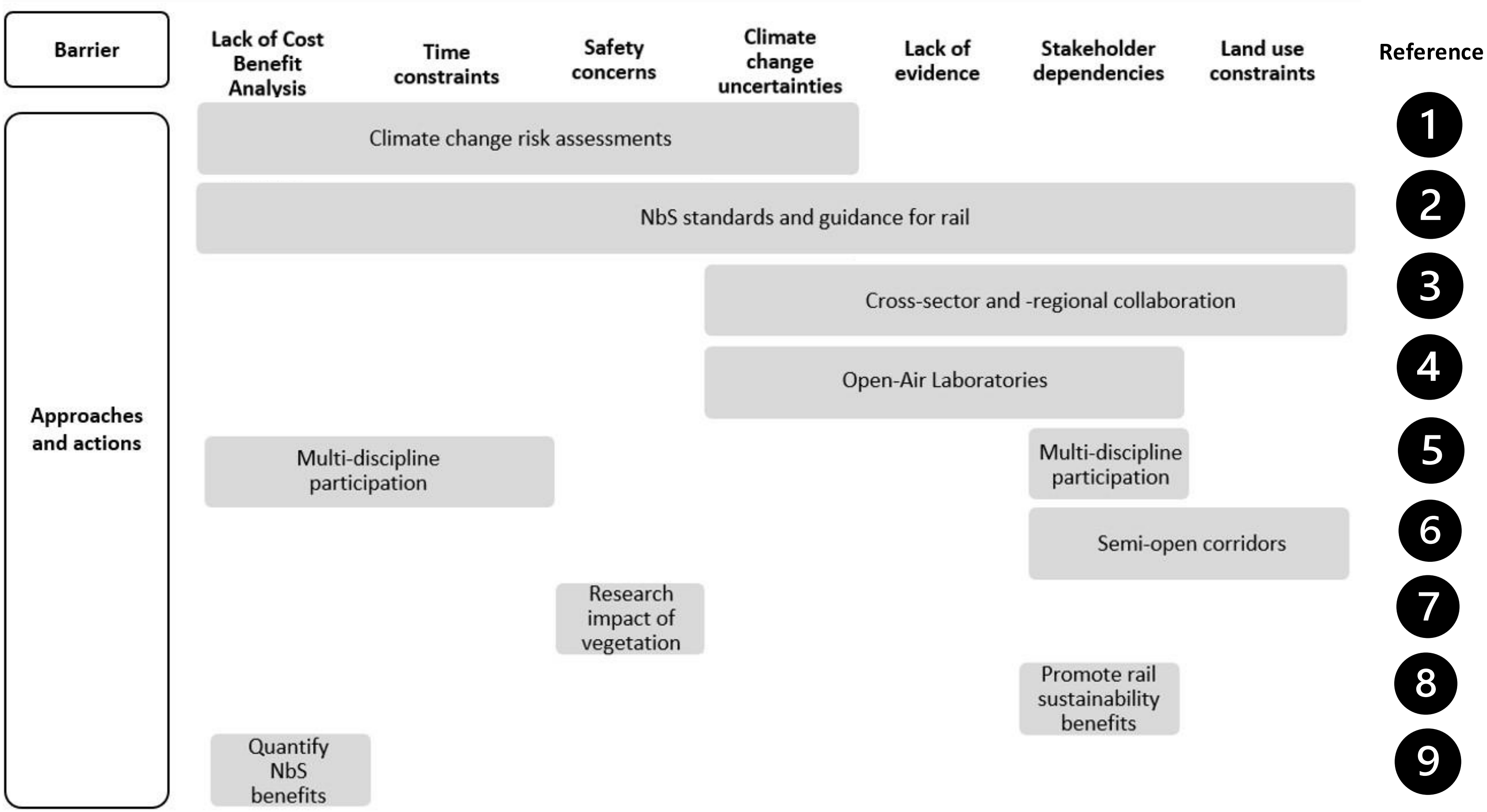

Figure 3-3 Approaches and actions that may support the implementation of nature-based solutions as climate change adaptation measures for railway infrastructure

The completion of a CCRA represents a critical step for CCA to be included in the lifecycle of rail infrastructure (Figure 3-4). Recognising that climate change is one of many risks that need to be considered in the management of rail infrastructure, CCRA should form part of a holistic risk management approach which considers the broader social, economic and environmental criteria associated with the provision of safe, secure and cost-effective rail services. The multiple ecosystem services and societal benefits that NbS can provide mean their use could contribute to the treatment of a range of rail industry risks i.e., not solely those related to climate change. For example, Transport for New South Wales (2017) recommend the use of green infrastructure as a deterrent to lineside vandalism and graffiti, thereby promoting the safety and security risk management credentials of an NbS approach. Figure 3-4 therefore depicts CCRA and the interlinked validation of NbS options for rail as being integral to wider rail infrastructure risk management.

At the early project planning stages, a CCRA can be used to inform the railway site or route selection and suitability (Network Rail, 2021b; Transport for New South Wales, 2016), and a Preliminary Design CCRA evaluation can enable the comparison of risk exposures between options (Network Rail, 2021b; Queensland Government, 2020). The later "Detailed Design" stage is, however, highlighted as the key intervention point, (Network Rail, 2021b; Queensland Government, 2020; Transport for New South Wales, 2016).

Phase	Process	Source
	Rail infrastructure risk management	Author
	Rail infrastructure lifecycle stage	California High-Speed Rail Authority (2021) Government of South Australia (2020) Network Rail (2017) Wordsworth (2019)
	Climate change risk assessment	Standards Australia (2013) The British Standards Institution (2019) Queensland Government, (2020) Transport for New South Wales (2016) Network Rail (2021)
	Validation of NbS options for rail	Kumar et al. (2020)
	Incorporation of NbS as CCA options for rail	Author
	Implementation of NbS in rail infrastructure	Author
1 to 9	Approach/action reference number	Figure 3-3 and Table 3-1

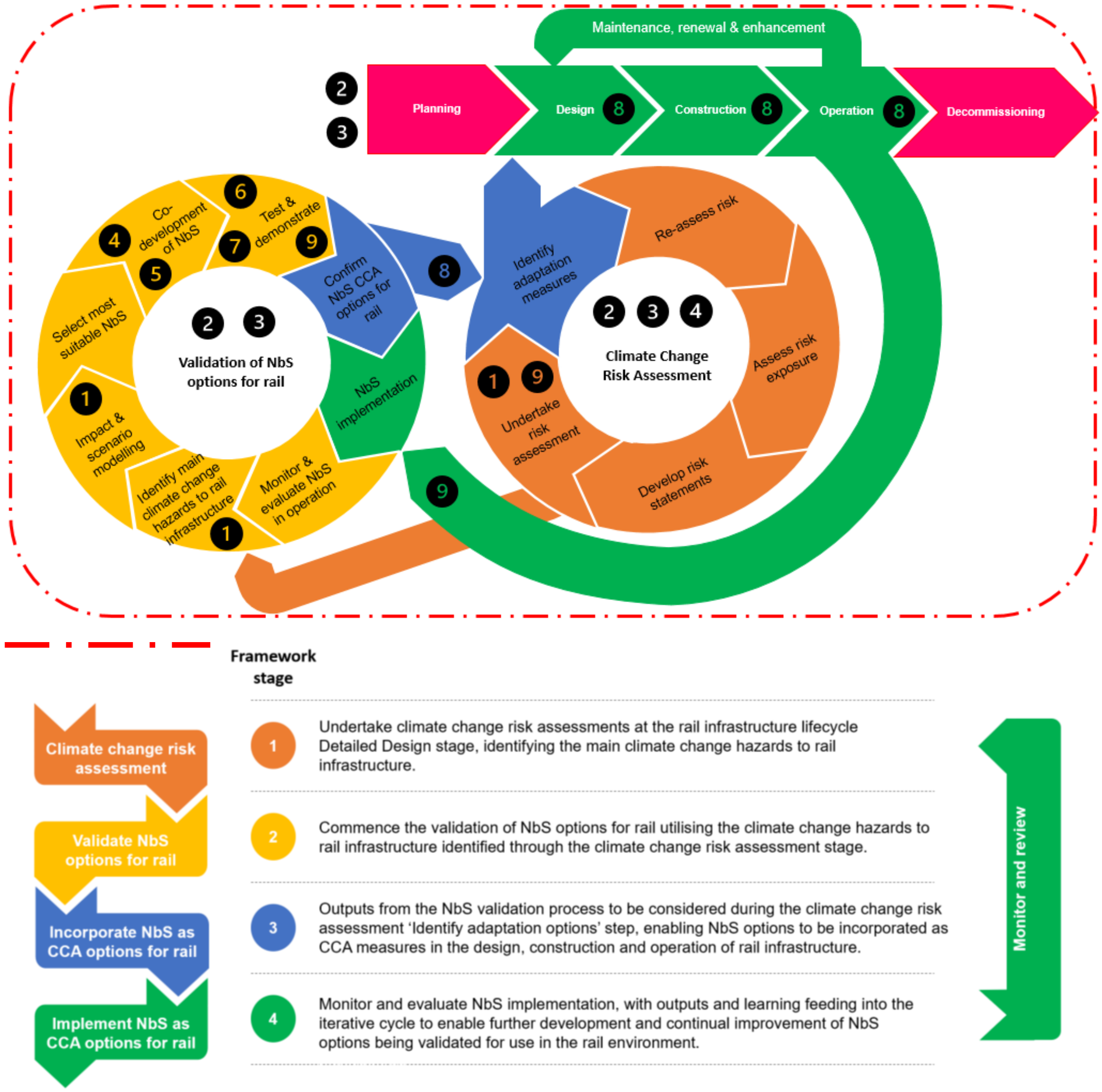

Figure 3-4 Framework to incorporate Nature-based Solutions as climate change adaptation measures for rail infrastructure

Table 3-1 Proposed approaches and actions to support the implementation of Nature-based Solutions as climate change adaptation measures for rail infrastructure
(Reference numbers relate to those in Figure 3-4)

Reference Number	Proposed Approach/Action	Description
1	Climate change risk assessment	As part of the holistic risk management of rail infrastructure, the CCRA process is key to the identification, analysis and evaluation of the risks posed by climate change. CCRA outputs inform the selection of appropriate risk reduction measures through adaptation options and thereby represent a vehicle by which to introduce NbS as CCA measures. The CCRA, and subsequent identification of CCA options, should consider the full lifecycle of railway infrastructure under various climate risk scenarios. The CCRA should address short- and long-term risks to facilitate an adaptative pathways approach, as well as considering the potential for maladaptation. In support of several of the other tools/actions listed below, and to reflect the capability of NbS to help treat railway risks in addition to those risks relating only to climate change, the CCRA should involve multiple disciplines and consider interactions with, and dependencies on, other sectors and stakeholders.
2	Promoting rail sustainability benefits	Advocating rail as a sustainable transport mode will help to harness public support for infrastructure investment, including the funding that will be required for CCA interventions such as NbS. Promoting the green credentials of rail along with the multiple ecosystem service benefits of NbS, which include human wellbeing and biodiversity benefits, could provide leverage when liaising with external stakeholders to encourage their participation in OAL and their sharing of, and/or provision of access to, land to enable semi-open corridor approaches,

Reference Number	Proposed Approach/Action	Description
		further supporting the implementation of NbS. Additionally, encouraging the use of rail over other means of transport will provide climate change mitigating benefits, helping to reduce the scale and frequency of HMH events.
3	Multi-discipline participation	The involvement of multiple stakeholders throughout the rail infrastructure lifecycle, CCRA and NbS validation processes will allow the sharing of complex information between parties in order to gain a common understanding of CCA planning and implementation for rail infrastructure, including insight into the adoption of NbS. Multi-discipline participation, for example in OAL and the development of semi-open corridors, will provide opportunities for knowledge transfer and shared learning, both internally with rail industry stakeholders and with external parties (e.g., neighbouring landowners, cross-sector peers) to help facilitate the wider-scale uptake of NbS.
4	Cross-sector and -regional collaboration	Opportunities exist for the rail industry to learn from and work with other transportation and linear corridor sectors to share CCA solutions, with joined-up approaches potentially enabling greater cumulative benefits. Similarly, this approach may help increase the resilience of utilities on which the railway is dependent (e.g., electricity and telecommunications). Learning from other industries and railway peers in other regions already experiencing the HMH likely to be faced in the future could help a region improve its readiness for predicted climate conditions.

Reference Number	Proposed Approach/Action	Description
5	Semi-open corridors	The use of NbS in the development of semi-open corridors extending beyond the railway boundary could help rail achieve CCA and biodiversity benefits despite having limited trackside land availability. The corridors will provide greater community and biodiversity benefits, augmenting rail's sustainability reputation and encouraging further investment as a green transport mode. This approach is also a mechanism for stakeholder engagement and building cross-sector relationships. The environments generated will support habitat connectivity, helping to maintain or potentially enhance species diversity, contributing to rail and wider community biodiversity targets as well as broader CCA and other ecosystem service benefits.
6	Open-Air Laboratories	On-site experimental evidence from successful railway demonstration sites will provide proof of concept to multiple stakeholders (internal and external to the rail industry); it will inform NbS standards and guidance for rail, quantify NbS benefits, and strengthen and help to promote the business case for NbS. Lessons may be learned from the OAL on the potential for maladaptation and how to maximise NbS performance.
7	Research impact of vegetation	Establishing safety standards to determine acceptable levels of trackside vegetation coverage, confirmed through robust evidence, may permit the presence of some vegetation on and/or adjacent to rail infrastructure, and therefore support the NbS concept for railways. The research could contribute to rail NbS standards and guidance (e.g., what can be planted where) and support the development of hybrid options, whilst also potentially informing options applicable to other sectors, thus enabling wider-scale NbS uptake and

Reference Number	Proposed Approach/Action	Description
		subsequent additional ecosystem service benefits. Further potential benefits include lower infrastructure maintenance costs, safety benefits for maintenance staff through their reduced exposure to the operational railway to tend to vegetation, as well as more aesthetic views for trackside neighbours and the travelling public.
8	NbS standards and guidance for rail	The development of NbS standards and guidance aimed at the rail environment will provide a valuable tool to aid the planning, design, maintenance and decommissioning of NbS for use on railway infrastructure. Based on the output of the NbS validation process, evidenced solutions could be presented in standards and guidance to support the comparison and selection of viable CCA options during the CCRA process. Noting that safety will be the most fundamental consideration, the standards and guidance could aid the choice of NbS based on factors including: the infrastructure or asset type being considered, the HMH(s) being faced, ground conditions, soil type and depth, site constraints (e.g., urban or rural setting), land take required, installation costs, vegetation establishment timeframes, and watering and maintenance required. The standards and guidance should consider all rail infrastructure lifecycle phases and the most effective combination of NbS per infrastructure type and the HMH(s) being faced, including hybrid grey-green solutions. The audience and intended users of the standards and guidance should be considered when developing material so that their needs and requirements may be addressed as comprehensively as possible; this could be tackled per railway

Reference Number	Proposed Approach/Action	Description
		engineering discipline or lifecycle phase, for example. The media selected to present and promote the NbS standards and guidance will also be vital in encouraging access and reference to the information produced.
9	Quantify NbS benefits	The use of multi-criteria analyses, completed by multi-discipline stakeholders, which capture and synthesise the full economic and wider sustainability benefits of NbS compared to alternative CCA measures over the full lifecycle of railway infrastructure will enable the consideration of NbS during the CCRA option comparison stage and support their potential to be selected and implemented. Data to inform NbS performance factors to be considered when comparing options may be gained through OAL. As funding will be required to incorporate CCA measures into the planning, design, and construction of new infrastructure and/or the enhancement of existing railway infrastructure, regardless of whether this involves green or grey adaptation solutions, the quantification of the economic costs and benefits of using NbS will be a very important step in demonstrating and presenting NbS as a financially attractive CCA option.

Detailed Design, which sees the completion of a robust engineering design, providing definitive costs, times, resources, and risk assessments (Wordsworth, 2019), is recommended as the project stage in which to incorporate climate risks into the rail project's or asset's overall risk management process (Queensland Government, 2020) and to embed adaptation actions into a project's design (Transport for New South Wales, 2016). A review of the CCRA process (summarised in Figure 3-4, orange phase) reveals the 'Identify adaptation measures' stage as a potential entry point for NbS. In order for NbS to feature as a prospective CCA option at this key stage, the NbS operationalisation framework proposed by Kumar et al. (2020) (as depicted in Figure 3-4) provides a mechanism for NbS to be confirmed as valid CCA options to be considered, and also present NbS as potential measures to treat further rail infrastructure risks including safety and security.

The long asset lives of rail infrastructure, typically designed to operate for over 50 years (and longer still, for some assets (Climate Adapt, 2019)), mean that it is appropriate to integrate CCA into long-term railway planning, design, and management processes. As well as being broken down into lifecycle stages, railway design and construction activities are also categorised by engineering discipline (Blackwood et al., 2022) and, subject to the type and scale of the infrastructure being designed, built, or enhanced, some or all disciplines may be involved; all will follow the rail infrastructure lifecycle process outlined in Figure 3-4. Embedding the completion of a CCRA as a mandatory stage in the rail infrastructure management lifecycle will therefore see CCA addressed during the asset's initial planning, design and construction and then followed up during the design and delivery of maintenance, renewal, and enhancement upgrades over its life.

3.5 Conclusion

There is a growing imperative for the rail industry to adapt its infrastructure to accommodate the impacts of both currently occurring extreme weather events and those anticipated under future climate change conditions. NbS are increasingly becoming recognised as a prospective means of delivering CCA provisions along with a host of further ecosystem service benefits. Although barriers to the uptake and implementation of NbS have been considered in other contexts, this review presents the findings of the first known research into their application in the railway environment. This study has categorised the primary barriers to the operationalisation of NbS as CCA options for rail infrastructure into seven key themes which include safety concerns, stakeholder dependencies, and land use constraints, whilst simultaneously establishing potential approaches and solutions which may facilitate the application of NbS, enabling the development of a proposed framework to aid their roll out. These findings highlight the need to develop NbS implementation standards and guidance for rail infrastructure, and, crucially, to embed CCRA in the rail infrastructure management lifecycle as part of the wider consideration of social, economic and environmental risks required to provide safe, secure and cost-efficient rail infrastructure. Whilst the promotion of CCRA for rail infrastructure will support the application of any type of CCA measure (grey, green or hybrid), further research efforts are required to support the validation of NbS options suitable for the railway environment. The co-development of solutions between researchers and rail professionals would support the progression of the multiple tools and actions this paper has suggested as enablers to the wider uptake and operationalisation of NbS as CCA measures for rail infrastructure, and potentially beyond, as the collaboration between science and rail practice may present opportunities for researchers to apply the learnings in other contexts.

This study is limited by the low number of live examples of NbS use in rail found in the literature, it therefore relies on literature which identifies barriers to the general implementation of NbS and to the application of broader CCA in rail, along with vegetation management issues faced by the industry. The list of barriers, and subsequent tools/solutions, may therefore not be exhaustive; consultation with rail professionals, the subject of ongoing research, will address this. The findings highlight several knowledge gaps. For instance, future research should be undertaken to identify and examine further examples of NbS in rail and include liaison with rail industry stakeholders to confirm their perception of the barriers to, and the issues that would influence their uptake of NbS, and to test the suitability of the proposed NbS implementation framework in the live rail environment.

Chapter 4 Rail industry knowledge, experience and perceptions on the use of nature-based solutions as climate change adaptation measures in Australia and the United Kingdom

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Abstract:

Nature-based solutions (NbS) have been identified as sustainable adaptation measures which could be applied to rail infrastructure in response to the impacts of climate change whilst also providing highly valued co-benefits. To date, however, only a limited number of examples of their use have been found in rail, and there has been little investigation into barriers to their uptake. We use an online questionnaire to examine rail industry professionals' knowledge, experience and thoughts in relation to perceived and/or actual obstacles to the use of NbS as climate change adaptation (CCA) measures for railways, and establish what could aid their wider implementation. This research confirms multiple examples of NbS being used in rail which are not included in the literature, and identifies a lack of awareness of NbS as the largest perceived barrier to their uptake. Education on and promotion of NbS in the industry will therefore be key to its successful widespread deployment. Policy, standards, and client specification were viewed as the best vehicles to enable greater NbS uptake; rail NbS case studies are therefore recommended as means of gathering robust evidence and examples to inform the development of these instruments. Demonstration sites could be used to inform rail stakeholders and communities to garner wider support for the concept. These may also be valuable to the work of researchers and practitioners investigating the wider development and deployment of NbS as sustainable CCA measures across wider (non-rail) sectors and scenarios.

Keywords: Nature-based solutions, rail infrastructure, climate change adaptation, sustainability

4.1 Introduction

Safe, reliable and affordable rail services support global economies, with railways providing a cleaner and more efficient means of moving freight to markets and people to employment and social amenities across countries and continents (Koks et al., 2019; The World Bank, 2022). Railway infrastructure is exposed and vulnerable to extreme weather (Koks et al., 2019; Lindgren et al., 2009; Network Rail, 2015), and with rising global surface temperatures projected to further increase and worsen the frequency and scale of extreme weather events (IPCC, 2021, 2022), there is a growing need for the rail industry to adapt to the impacts of currently-faced weather events, and the conditions anticipated in future climate conditions (Davies et al., 2014; Marteaux, 2016). Notwithstanding a rapid growth in literature on climate change impacts on transport infrastructure and operations, research on climate threats and subsequent adaptation approaches for the rail industry is scant (OECD, 2018; Wang et al., 2020a). The ability of railways to maintain operations during extreme weather conditions and recover from these quickly is crucial to ensure the continued provision of safe and dependable services (Koks et al., 2019; Nolte, n.d.). Climate change adaptation (CCA) is therefore a complex and urgent challenge in the management of rail infrastructure (Davies et al., 2014), as confirmed by the United Nations Economic Commission for Europe Group of Experts on Climate Change Impacts and Adaptation for Transport Networks and Nodes (UNECE, 2018).

The Intergovernmental Panel on Climate Change (IPCC) defines adaptation as "the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities" (IPCC, 2023, p. 2898). Three basic approaches to adaptation can be identified: Retreat (or avoid), Protect (providing a physical barrier to protect the infrastructure), or Accommodate (adapting the infrastructure itself) (Eichhorst, 2009). These approaches are illustrated in Figure 4-1 in the context of adaptation to sea level rise; however, in general they are applicable to all climate change impacts.

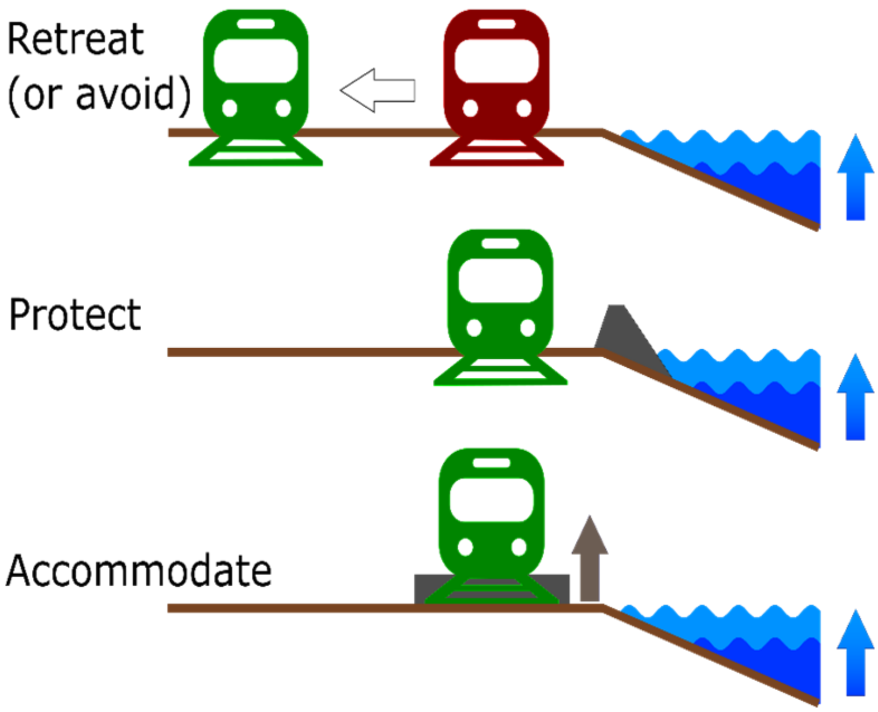


Figure 4-1 Three fundamental approaches to adaptation

Adapted from Eichhorst, 2009

In addition to the three above approaches, adaptation to climate change can incorporate a variety of possible actions (Jones et al., 2012). Alongside 'soft' management interventions such as early warning systems for extreme weather events, the predominant rail industry responses to climate-induced impacts involve 'grey' engineered solutions (Blackwood et al., 2022), including concrete flood walls and overflow channels, for example. There has been increasing recognition that 'green', nature-based solutions (NbS), such as green (vegetated) walls and natural drainage systems, can supplement grey measures (Seddon et al., 2020b), thus creating hybrid options which potentially provide optimal, more sustainable solutions, especially when co-benefits are considered (Fink, 2016;

Ruangpan et al., 2020). For example, using vegetation alongside concrete drainage installations would bolster the CCA intervention's protection against and accommodation of anticipated increases in rainfall and flood events, and in addition, the NbS would improve water quality, help stabilise embankments, and provide a barrier to the dispersal of pollutants (Blackwood et al., 2022). By directly addressing societal challenges such as disaster risk reduction and climate change adaptation, NbS solutions can intrinsically contribute to sustainable development (Cohen-Shacham et al., 2019). Whilst humans have historically applied natural solutions in response to climatic variability (Jones et al., 2012), the profile of NbS has increased significantly in recent years and the body of research conducted on its application in response to the impacts of climate change has grown rapidly (Seddon, 2022). Despite considerable research having been conducted on NbS implementation in cities and urban areas (Frantzeskaki et al., 2019), studies on its use on railways have remained scarce (Blackwood & Renaud, 2022; Blackwood et al., 2022).

A literature review found five examples of NbS in place on rail infrastructure globally, all of which involved the use of vegetated solutions in response to high precipitation causing flooding and/or an increased risk of erosion and landslides, along with multiple examples of NbS implemented in non-rail contexts which may be transferable to the rail industry (Blackwood et al., 2022). For example , such NbS concepts include green walls, natural drainage solutions, reefs and mangroves, (see e.g., Cohen-Shacham et al., 2016; Eisenberg & Polcher, 2019). It is acknowledged that NbS remain a relatively new concept (albeit with a very rapid uptake) and, due to the potential lack of understanding over what NbS are (Sarabi et al., 2019), further examples may be in place in the rail environment without being labelled as such (Blackwood et al., 2022). The limited literature on NbS practices in rail, combined with the general scarcity of scientific data on rail CCA (OECD 2018; Wang et al., 2020a) may be due to the rail industry prioritising the implementation of immediate operational responses to extreme weather events rather than research longer-term solutions (Blackwood et al., 2022); this may be exacerbated by rail organisations generally not employing in-house CCA experts, whilst climatologists and meteorologists are not railway experts (Quinn et al., 2017). The identification of additional instances of NbS application in rail will therefore help promote the NbS concept and may encourage its wider uptake.

The adoption of NbS on railway infrastructure relies upon the acceptance of the concept by rail industry stakeholders including those who design, construct, operate and maintain rail infrastructure; it is also dependent on these parties' implementation of climate change risk assessments (CCRA) to identify the need for and to implement CCA of any form (soft/grey/green/hybrid). The likely barriers to NbS implementation by railways as found in the literature include safety concerns, land use constraints and stakeholder dependencies (Blackwood & Renaud, 2022). Despite these challenges, due to railways' need to implement sustainable, long-term and cost-effective CCA solutions, investigation into the suitability of NbS application on rail infrastructure warrants further exploration, with Blackwood and Renaud (2022) recommending measures to support the development of the NbS concept in the rail environment. This research engaged with rail professionals to examine industry awareness on, examples of and attitudes towards the use of NbS as CCA measures for railway infrastructure, guided by the following research questions (RQ):

RQ1: Are there NbS being used as CCA measures in rail which are not included in the literature?

RQ2: What are the challenges and barriers to the operationalisation of NbS as CCA measures for the rail industry?

RQ3: What could aid the operationalisation of NbS as CCA measures for the rail industry?

An online survey was distributed to railway professionals to gauge their knowledge, experience and thoughts in relation to these issues. The questionnaire was also used to ascertain levels of rail industry CCRA practice and awareness levels on general CCA measures, to help establish whether processes currently used may lend themselves as vehicles to implement NbS more widely. A parallel mixed methods approach was applied to combine the collection and integration of both quantitative and qualitative data, whereby closed questions enabled the quantitative measurement and description of trends, attitudes and opinions, whilst qualitative data gained through open ended questions added richness to the survey results (Creswell & Creswell, 2018; Krosnick & Presser, 2010). Results are structured based on the above three research questions. As there has been extremely limited research conducted on the subject to date (Blackwood et al., 2022), this study therefore gathers important new primary data and information which may inform and promote practical CCA options for the global rail industry to sustainably protect its infrastructure from, or adapt it to accommodate, the impacts of a changing climate. The outputs may also support the work of researchers and practitioners investigating the wider development and deployment of NbS and/or CCA measures across wider (non-rail) sectors and scenarios.

4.2 Methods

Between 10-31 May 2022, participants were provided with an anonymous link to a web-based survey which was administered using Jisc Online Surveys (Jisc, 2023). The full questionnaire may be viewed in supplementary text S1 [**Appendix B**]. Purposive sampling was undertaken by targeting invitations and requests to participate to key stakeholder categories who are, or should be involved in CCRA for railway infrastructure (Infrastructure Sustainability Council, 2021a; Transport for New South Wales, 2016). The intended audience for the questionnaire was confirmed via letter to gatekeepers in national (UK) and State/Territory (Australia) rail organisations, who were asked to distribute a link to the survey and invitation to participate within their respective corporations. The authors did not have visibility of the onward distribution of the invitation to participate. Contacts known to the lead author, who has over 15 years' experience in railway infrastructure sustainability in the UK and Australia, were also sent the survey link. This approach was supplemented by snowball sampling, with participants sharing the survey weblink with their colleagues and peers. Ethical clearance for data collection was granted by a dedicated panel at the University of Glasgow, College of Social Sciences. Data on participants' job title and length of rail industry experience was requested to evaluate their level of experience and, when combined with the high quality of responses provided to all other questions in the survey (e.g., all questions answered and detailed feedback provided in free text fields, using rail-specific terminologies), helped to confirm the validity of the input from all participants. All responses were voluntary and treated anonymously, with the survey being designed to prevent the identification of participants. The survey was pre-tested through distribution to three rail industry professionals.

To help focus survey responses, the question set was aligned with the three primary RQs, as shown in Table 4-1. The ten NbS concepts included in the question set to address RQ1 were those which had been proposed by Blackwood et al. (2022) as potential alternatives and/or complements to the CCA measures currently adopted by the rail industry to protect its infrastructure from or adapt it to accommodate climate change impacts. The ten concepts selected use existing NbS terminologies identified through a literature review conducted to establish NbS implemented in both rail and non-rail environments (refer to e.g., Transport for New South Wales, 2017; UNaLab, 2019), meaning that survey participants may have awareness of the concepts and have been involved in their application outside of the railway context. Identifying railway examples of the application of the ten concepts, and/or confirming high levels of awareness of their application in rail would help to confirm the validity of the NbS alternatives and complements that have been suggested.

For questions on perceived NbS effectiveness 'I don't know' response options were provided. Whilst doing so may encourage satisficing (Krosnick & Presser, 2010), because NbS are a new concept respondents may not have sufficient knowledge or information on which to form an opinion on the success of their performance. Further, due to the nature of rail infrastructure management, survey participants may only be involved in a short window of an asset's lifecycle (e.g., its design and/or construction) and therefore may not have visibility of NbS or CCA measures in use, particularly as some roles may be performed at considerable distance from the asset's location, meaning that a participant may genuinely not know how well an NbS performed. 'I don't know' responses were treated as mid-point responses for the perception-based questions; otherwise, 1-4 scaled response options were provided in order to force an opinion, with low scores representing the lowest level of awareness or involvement, as appropriate.

Table 4-1 Alignment of survey methods with research questions

<table>
<tr><th rowspan="2">Research question</th><th colspan="2">Survey methods</th></tr>
<tr><th>All participants (n = 55)</th><th>Where participant confirms awareness of or involvement with the use of NbS on rail infrastructure</th></tr>
<tr><td>1. Are NbS being used as CCA measures in rail which are not included in the literature?</td><td>• Quantitative question to determine awareness of general CCA for rail infrastructure.
• Forced 1-4 Likert responses to determine levels of familiarity with ten NbS concepts.</td><td>• Funnelling of questions with quantitative and qualitative responses sought to obtain details on NbS usage.</td></tr>
<tr><td>2. What are the challenges and barriers to the operationalisation of NbS as CCA measures for the rail industry?</td><td>• Quantitative questions to establish current levels of CCRA undertaken and, where completed, their scope.
• Selection of top 3 barriers from predetermined list.
• Qualitative field also provided to allow description of additional barrier(s).</td><td>• 1-4 Likert responses with an ‘I don’t know’ option to record perceived NbS performance as CCA measure to determine rail attitude towards and appetite for the use of NbS as CCA measures.
• Qualitative field also provided to allow description of perceived problems.</td></tr>
<tr><td>3. What could aid the operationalisation of NbS as CCA measures for the rail industry?</td><td>• Selection of top 3 enablers from predetermined list.
• Selection of top 3 support mechanisms from predetermined list.
• Qualitative field also provided to allow description of additional:
○ Enabler(s)
○ Support mechanism(s).</td><td>• 1-4 Likert responses with an ‘I don’t know’ option to record perceived NbS performance as CCA measure to determine rail attitude towards and appetite for the use of NbS as CCA measures.
• Qualitative fields also provided to allow description of:
○ Additional benefits gained
○ Learning points obtained</td></tr>
</table>

Detailed descriptions of the ten NbS concepts were not provided in the questionnaire to avoid skewing results through participants claiming they were aware of a concept(s) they had not heard of previously. The provision of descriptions, however, may have enabled the distinction to be made between each concept, failure to do so does mean that people may have mixed up NbS concepts. Participants may therefore have stated awareness of the earliest featured NbS when later concepts may have been more appropriate. Even if responders realised this, they may not have known how to work back through the questionnaire to update their answers (even though this was possible) or wanted to take the time to do so. Participants may also have failed to recognise NbS concepts they are familiar with but refer to using a different terminology; by not seeing NbS nomenclature they are accustomed to included in the questionnaire, some levels of awareness may be higher than indicated.

Data pre-processing was carried out using Microsoft Excel and statistical analysis performed using IBM SPSS Statistics (Version 28.0). A Shapiro-Wilk test determined that the data from Likert items were not normally distributed; a subsequent non-parametric Mann-Whitney U Test showed that there were statistical differences between the means of UK and Australian data. Thematic coding of qualitative data was conducted using NVIVO 12.

4.3 Results and discussion

Results are discussed below in alignment with the three primary RQs. Due to the purposive sampling employed, the 55 responses received were dominated by participants from the UK (60%) and Australia (33%); the majority of these were environment and sustainability professionals (53%), followed by those in project management (13%), and the Health & Safety and Engineering disciplines (each representing 7% of responses). The participants' organisations represent a range of rail industry functions and their associated supply chains, including infrastructure owners, operators and maintainers, along with rail infrastructure designers, constructors and support consultancies. Over half of the respondents had at least 10 years of rail industry experience, 27% of participants had 10-19 years' experience and a further 27% had over 20 years. Although there was a relatively small number of survey participants, reflective of the purposive sampling employed to target a very niche group of rail industry stakeholders, the quality of the responses received from experienced industry professionals contributes significant value to this research topic. Survey responses could only be submitted upon completion of all questions, i.e., there were no partially completed responses. Whilst quantitative data is presented in the following sections, the small sample size does however mean that the outputs remain largely qualitative.

4.3.1 RQ1 NbS being used as CCA measures in rail which are not included in the literature

The levels of participant awareness of ten NbS concepts are shown in Figure 4-2. Using the means of the responses provided for each of the ten concepts to establish overall NbS awareness (i.e., the total level of awareness across all ten NbS), 11% of participants were aware of the concepts being used in rail, and 6% had been directly involved in the use of NbS as CCA measure on rail infrastructure, 63% of responders were aware of NbS concepts but not their application in rail, and the remaining 20% (1 in 5) had never heard of the concepts.

Survey responses demonstrated 61 instances of participants being aware of, and 35 cases of being directly involved in the use of NbS as CCA on rail infrastructure. Participants had most awareness of and involvement in the application of the natural drainage, green corridor and the use of vegetation to protect assets/infrastructure concepts. Green walls were the most recognised NbS with only 3 respondents having never heard of this concept; salt marshes and bioengineering/biotechnical solutions were the least familiar, with no known examples of use in the rail environment being provided for either.

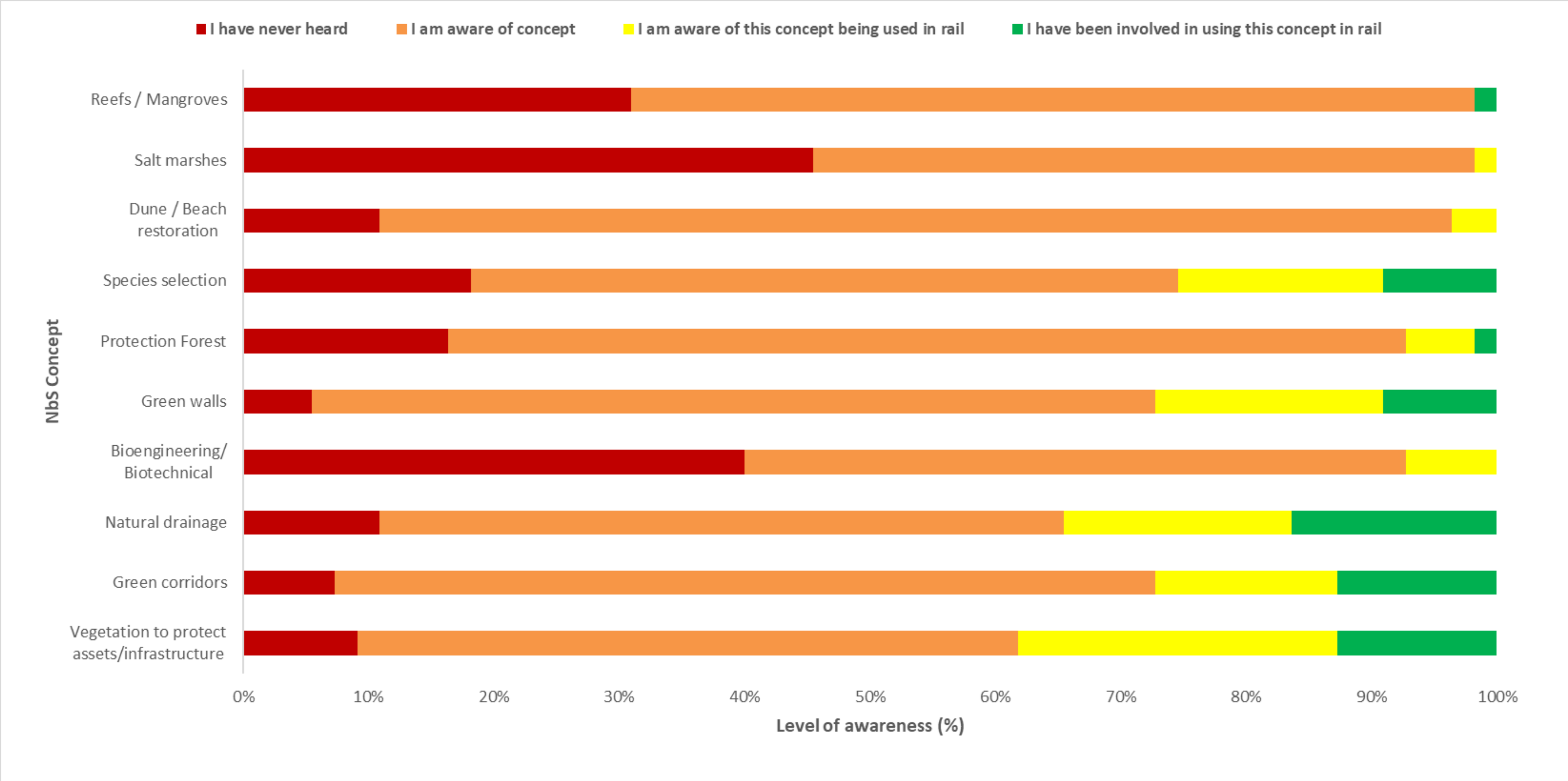
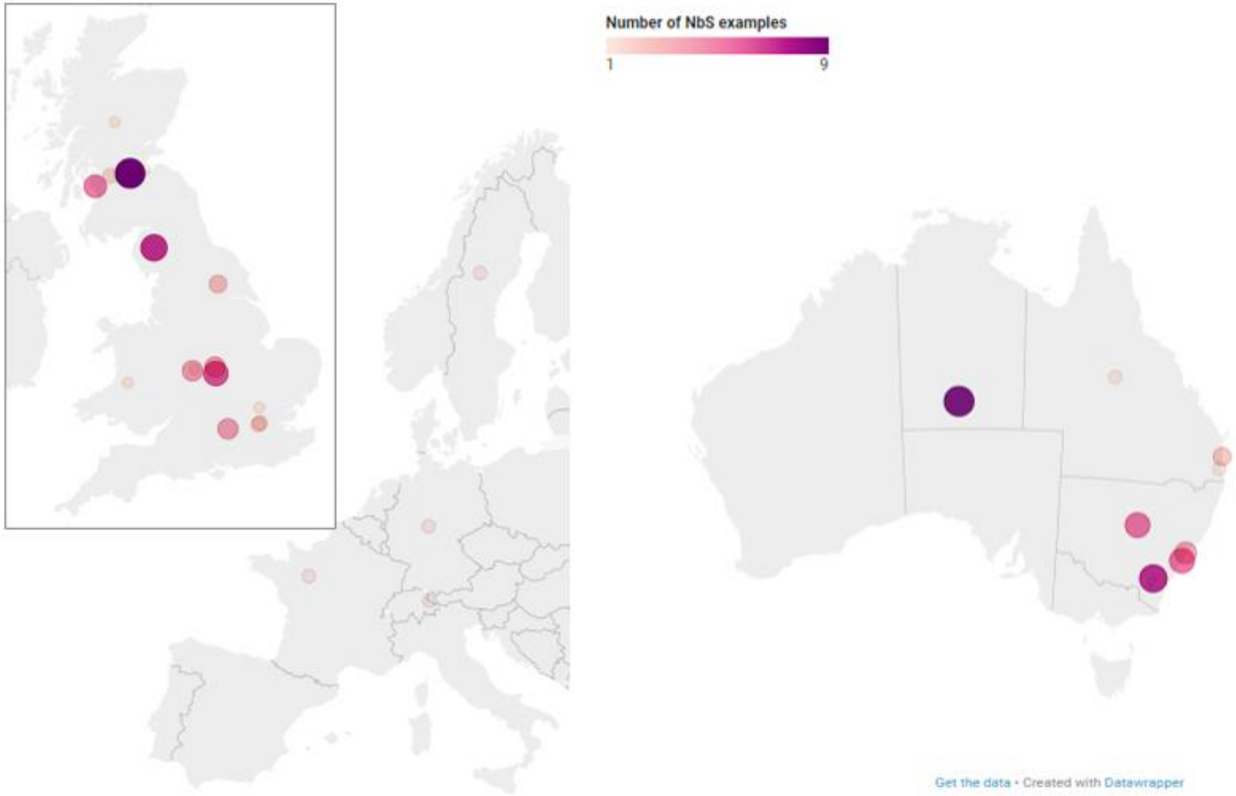


Figure 4-2 Survey participant awareness levels of ten NbS concepts

Participants were asked to detail the location(s) of known NbS examples; some answers provided multiple locations per NbS concept, some provided none. Where locations were provided, some were specific (e.g., "Queen Street Tunnel, Scotland") whilst others were vague (e.g., "Australia-wide"). As a further reflection of the purposive sampling method, most instances are either in the UK (66%) or Australia (28%). The locations are mapped in Figure 4-3 (a) and (b), with markers for answers that were quoted at a country or regional level being placed at the centre of the jurisdiction as per the geographic granularity provided in each response. Figure 4-4 provides an overview of the location of each NbS concept by country; one location described by a survey participant as "abroad" has not been mapped.



(a) (b)

Figure 4-3 Distribution of NbS in rail examples in (a) Europe (b) Australia

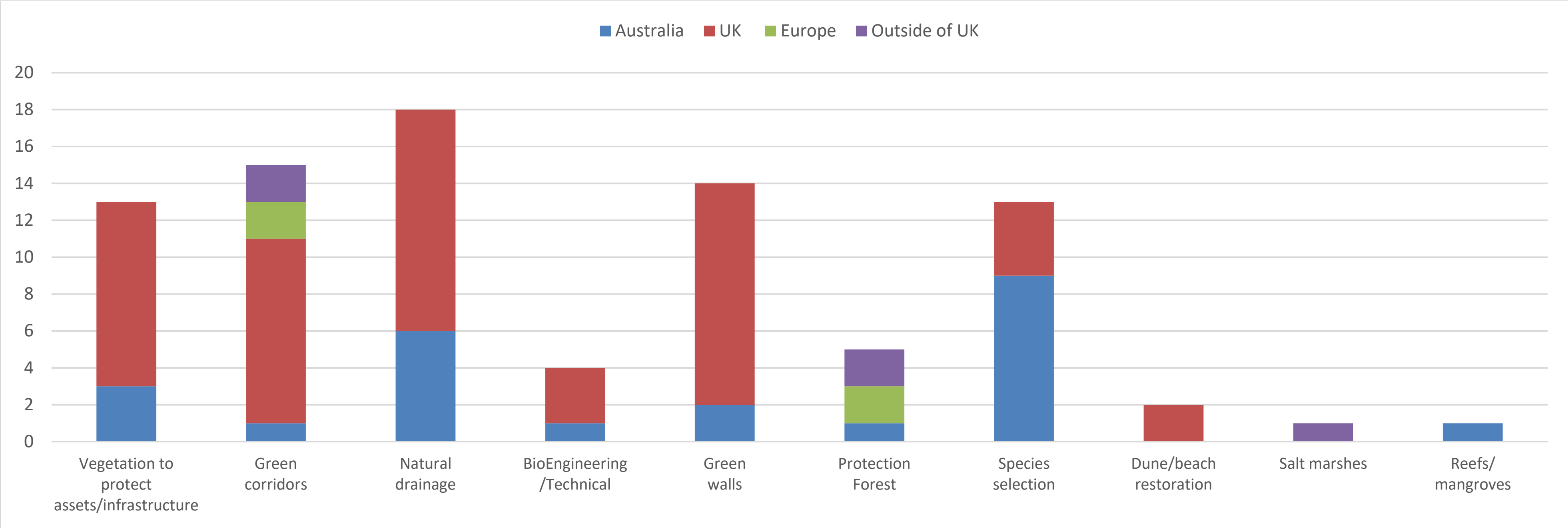


Figure 4-4 Locations of NbS concepts by type

Of the 81 responses which included NbS locations, participants referenced 25 specific sites, i.e., at suburb level or named rail infrastructure location or asset, which enabled the identification of distinct NbS examples. This was not possible when a country or region-wide response was provided however, which means that there may be duplication in the recording of examples in Figure 4-3 (a) and (b). For example, one London NbS case may have been cited at the local city, England, Great Britain and UK levels, resulting in it potentially being counted up to four times. On the other hand, participants may have been aware of multiple examples at a regional or country level but did not reflect this in their response, leading to under-counting. The High Speed Two ("HS2") Route in the UK, for instance, was cited nine times across all survey replies; these have been recorded as nine separate responses rather than being rolled into one. Whilst this may be regarded as duplication, HS2 examples were referenced by three participants across five different NbS concepts, with one respondent providing a link to the HS2 "Green Corridor online mapping tool" which provides details of multiple examples of green corridor and associated NbS features along the length of the new high-speed line being constructed between the West Midlands and London, UK (H. S. Ltd, 2022). The new railway is currently under construction (H. S. Ltd, 2021), meaning that many NbS are planned rather than operational, and therefore awareness of their presence may not yet be widespread, with the implication that, in later survey questions, responses cannot yet be given on their perceived performance. It should be noted that it may be easier to design and build NbS features into new infrastructure that is under construction, rather than retrofit measures into existing rail infrastructure. Given the land take that may be required to install NbS at a sufficient scale (Albert et al., 2019; Sarabi et al., 2019; The Royal Society, 2014), the retrofitting of NbS (and/or other CCA measures) could be particularly difficult in urban areas, where space is at a premium (Sarabi et al., 2019). The prominence of HS2 as the largest-scale rail infrastructure project currently underway in the UK introduces the potential for availability bias. The high number of NbS features included in the HS2 Green Corridor online mapping tool confirms the HS2 project to have significantly more documented NbS examples than have been found for other projects. As only three participants cited HS2 examples of NbS on rail infrastructure (representing 5.5% of survey respondents), their input is not regarded to have an unreasonable bearing or skew on the outputs of this research. Where participants responded that they had been directly involved in the use of NbS in rail, it could be assumed that they would be better placed to provide more detailed answers to the 'free text' questions. This was not necessarily the case. For example, 68% of respondents who had awareness of NbS in use provided a specific location, whereas only 61% of those who claimed to have been involved in the use of NbS concepts did so. Direct involvement, however, may infer greater confidence in the quality of responses.

In their literature review, Blackwood et al. found five examples of NbS in use in the rail environment, one in London, UK and four in or near Sydney, Australia (2022). Only one location that featured in the literature review (Bermondsey Dive Under, London, UK) was directly referenced as an example of NbS by a survey participant. None of the four Sydney locations included in the literature (Cronulla, Turella, Cabramatta and Coalcliff) were directly quoted in the survey responses, and the four questionnaire answers citing Sydney examples referred to specific locations (Parramatta, Leppington & Edmondson, Castle Hill and Mortdale); i.e., four additional locations to those included in literature. The literature review scope (Blackwood et al., 2022) was heavy rail infrastructure, and did not include light rail or station buildings; the survey questionnaire did not feature these limitations however, and results included 6 references to light rail infrastructure; Birmingham New Street Station was cited 4 times, with answers not specifying whether they related to the building or rail infrastructure within its locale.

Whilst the limitations outlined above make it difficult to precisely confirm the number of NbS being implemented as CCA measures in the rail industry, the examples cited by survey participants indicate that, in answer to RQ1, there is a greater number, at a wider range of locations, than are currently included in the literature. It is likely that further examples of NbS are being used in the rail environment which are not recognised or labelled as such; these may include NbS concepts with different names to those applied in this study meaning that examples survey participants were familiar with were not recorded. Similarly, the limited inclusion of rail NbS examples in scientific or grey literature may be reflective of NbS still being a relatively new concept in rail and, where they are implemented, they are not documented as NbS (Blackwood et al., 2022). Further, rail industry priority may be to initiate immediate operational responses to extreme weather events (Blackwood et al., 2022) rather than spending time and money researching and writing about these; particularly if their responses do not deliberately include or explicitly reference CCA measures (Lindgren et al., 2009). In addition to helping determine whether there were any (or any additional) live examples of use of the ten NbS concepts in the rail environment, the process of assessing their familiarity with each concept may have increased survey participants' awareness on the potential for NbS to be applied as CCA measures in rail, and/or this may have helped to demonstrate the potential transferability of the infrastructure protection and adaptation concepts from non-rail to rail scenarios which participants may not have previously considered.

Participants who were aware of and/or involved in the use of NbS in rail were asked to confirm the climate change hydrometeorological hazard(s) (HMH) in response to which each concept was being applied. Figure 4-5 confirms that high precipitation was the most addressed HMH (51 instances); this correlates with the literature review findings of Blackwood et al. (2022). High temperature was the HMH with the second highest number of responses (33 instances), although it is recognised that it is the human-induced increase in global surface temperatures that is affecting weather and climate extremes worldwide (IPCC, 2021) i.e., high temperatures are exacerbating the other HMHs (except lightning) and therefore rail infrastructure responses to all other HMHs can infer an indirect CCA response to high temperatures also. Survey responses detailing the HMH(s) that each rail NbS example was being used to address generally align with the potential NbS applications suggested by Blackwood et al., strengthening the recommendations made for NbS alternatives and complements (2002).

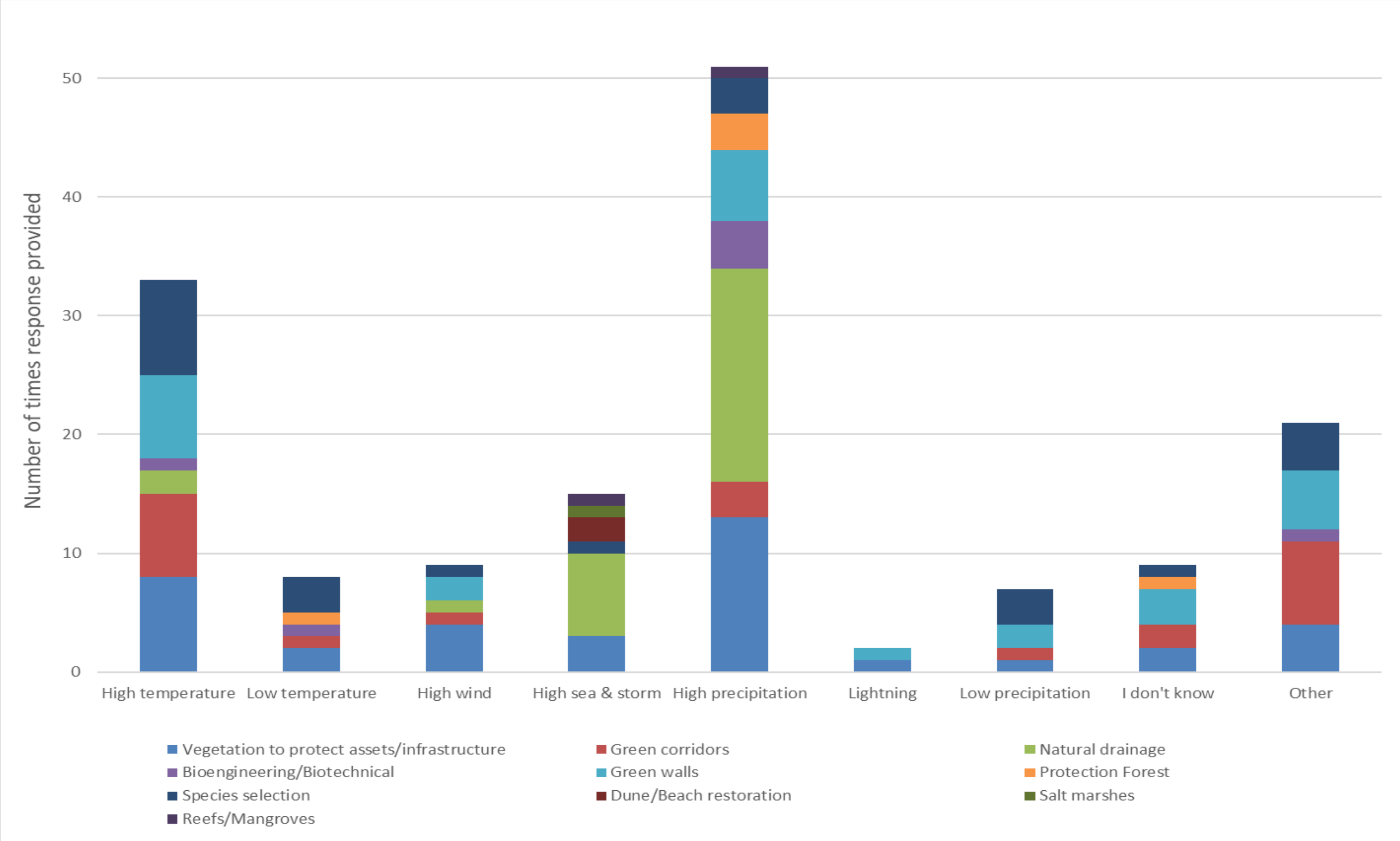


Figure 4-5 Natural hazards NbS are being used to address

4.3.2 RQ2 Challenges and barriers to the operationalisation of NbS as CCA measures for the rail industry

Questioning on the completion of CCRA established that 7% of participants never, and 15% rarely undertake these assessments during the planning, design, construction and/or operation of new or when upgrading existing railway infrastructure. With CCRA identified as a critical activity to incorporate CCA measures in rail infrastructure (Blackwood & Renaud, 2022), this means that almost one in every four rail projects may not introduce CCA of any type to protect or adapt infrastructure. As well as raising concern over the long-term resilience of new infrastructure, this presents an immediate barrier to the uptake of NbS for this purpose.

A lack of awareness of the ten NbS concepts featured in the survey (Figure 4-1 "I have never heard" responses) was verified via a direct question asking participants to select from a predetermined list their top three perceived barriers limiting the uptake of NbS. Responses are presented in Table 4-2 where 'Lack of NbS awareness' is confirmed as the top barrier, with 20% of responses. Combining this with the 'Lack of NbS rail awareness' which received 6.7% of responses, it means that an overall lack of awareness on NbS concepts is the key barrier to the operationalisation of NbS as CCA measures, with over one quarter of rail industry survey participants citing this reason. Rail industry resistance to change was the second most selected barrier. The path dependency of stakeholders is a recognised barrier to the general deployment of NbS (Davies & Lafortezza, 2019; Frantzeskaki et al., 2019), and the results of this survey help to confirm that the path dependence of railway engineers, with their resistance to changes to long-standing grey engineering traditions, is a particularly difficult sector-specific challenge for NbS to overcome (Blackwood & Renaud, 2022).

Barriers to NbS uptake were also determined indirectly by asking participants with knowledge of or involvement in the implementation of NbS in rail (n = 61 and n = 35 examples, respectively) about any problems that they encountered during their use of each NbS concept. 83 problems were cited from respondents located in three countries (n_{Other}= 3, $n_{Australia}$= 36, n_{UK}= 44). Coded responses, collating answers from all ten NbS concepts, are presented in Figure 4-6 which groups responses into 18 key themes. 'Lack of awareness' did not feature in responses to this screened question directed only to those with knowledge or experience of applying NbS in rail but otherwise, with extra maintenance requirements and poor maintenance practices being the most commonly cited problems observed, and culture change also featuring heavily, these outputs again generally correlate with the top barrier findings shown in Table 4-2 (“Rail resistance to change”).

Table 4-2 Top barriers limiting the use of nature-based solutions as climate change adaptation options for rail

Barriers	**Responses**	
	N	**%**
Lack of NbS awareness	33	20.0
Rail resistance to change	23	13.9
Maintenance	20	12.1
Lack of Cost Benefit Analysis	18	10.9
Lack of regulation/standards	15	9.1
Cost	13	7.9
Lack of NbS rail awareness	11	6.7
Safety concerns	8	4.8
Time to grow	7	4.2
Limited land	7	4.2
Third party stakeholders	5	3.0
Climate change uncertainty	3	1.8
Other	2	1.2
Total	**165**	**100%**

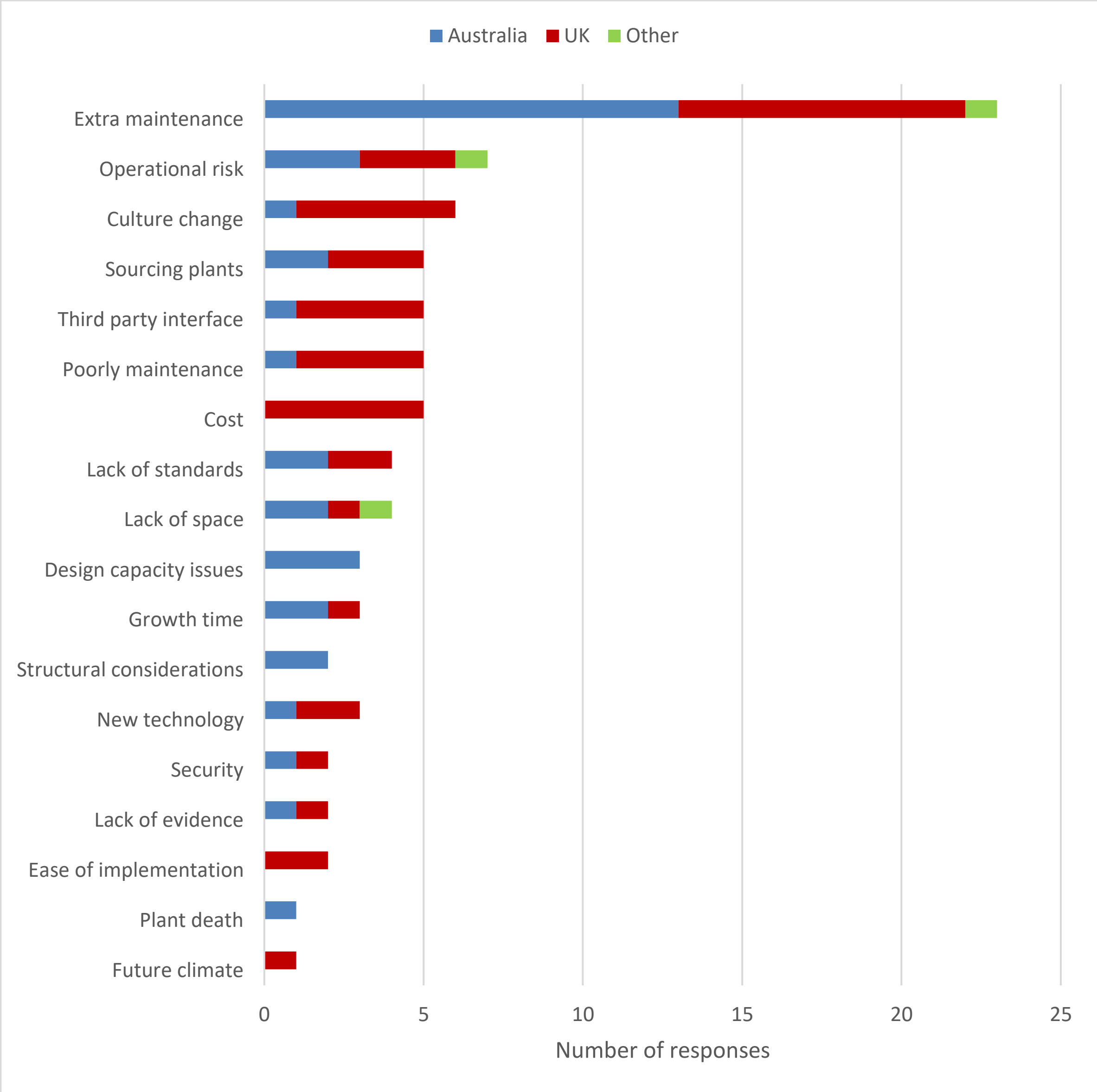


Figure 4-6 Problems encountered in NbS implementation on rail

Recognising the contrasting climates, land use patterns and rail industry structures between and within the countries represented in this survey, responses confirm agreement from participants from all geographies on the top two barriers, and there was affirmation of barriers from both Australian and UK respondents over 13 of the 18 themes. The small number of responses received prevents detailed analysis of the results. However, general observations include that culture change and cost were regarded as bigger issues in the UK, whilst Australian participants highlighted the more technical practicalities of NbS design (i.e., capacity and structural considerations).

4.3.3 RQ3 Aids to the operationalisation of NbS as CCA measures for the rail industry

Over half of respondents “Often” or “Always” conduct CCRA when planning, designing, constructing and/or operating rail infrastructure or when upgrading existing assets, thus presenting the completion of CCRA as a strong mechanism to implement CCA in the first instance, and encourage that these include NbS. Participants were asked to choose from a pre-determined list the top three measures they believe would enable the widespread uptake of NbS as CCA measures in rail; responses are presented in Table 4-3 by country for Australia and the UK (Table 4-3 data excludes the responses from four participants out with these locations). Even with the differing regulatory and rail industry structures implemented in each jurisdiction, Table 4-3 shows that the use of Legislation, Policy and Standards and Client specification were the most selected options in both countries. These approaches align with the ‘stick versus carrot’ practice often observed in cultural change management, where prescribed, compliance-based requirements are set to mandate a change in behaviour in organisations with low sustainability maturity levels (Baumgartner & Ebner, 2010).

Table 4-3 Top measures to enable widespread uptake of NbS

Enablers	**Australia Responses**		**UK Responses**	
	N	**%**	**N**	**%**
Legislation	13	24.1	20	20.2
Policy & Standards	12	22.2	20	20.2
Client specification	12	22.2	19	19.2
Education	9	16.7	11	11.1
Funding/incentives	3	5.6	15	15.2
Cost Benefit Analysis	4	7.4	11	11.1
Landowner partnerships	1	1.9	3	3.0
Total	**54**	**100%**	**99**	**100%**

A further means of aiding NbS implementation would be to promote the usage benefits reported by rail industry users, as gleaned from those with knowledge of and/or involvement in the use of NbS as CCA measures on rail. Coded feedback collated across all ten NbS concepts is shown in Figure 4-7. 108 benefits were cited, from participants located in either Australia (n=50) or the UK (n =58). Biodiversity gains were the most reported benefit, followed by Aesthetics and Improved drainage. Coding of the survey responses identified 24 key themes versus 18 problem areas (Figure 4-6) which, combined with the larger number of benefits than problems quoted (108 versus 83), can be seen as a reflection of the recognition of the multiple wide-ranging benefits of NbS. There is alignment in Australian and UK responses for the top 9 benefits, demonstrating the international recognition of these benefits.

Figure 4-7 confirms the multiple sustainability benefits that NbS can deliver, and, as suggested by Blackwood et al. (2022), demonstrates that the use of NbS could therefore help the rail industry contribute to the United Nations 2030 Sustainable Development Goals (United Nations, 2021a), particularly “Life on Land”, by using NbS to conserve, restore and sustainably use land and its ecosystem services to support the “Industries, Innovation and Infrastructure” goal of providing reliable, sustainable and resilient infrastructure (United Nations Global Compact, 2019). These additional benefits could also support rail’s achievement of ambitious sustainability objectives including “no net loss” and “net positive” biodiversity targets (H. M. Government, 2019). Promotion of these benefits could therefore significantly aid the operationalisation of NbS as CCA in rail.

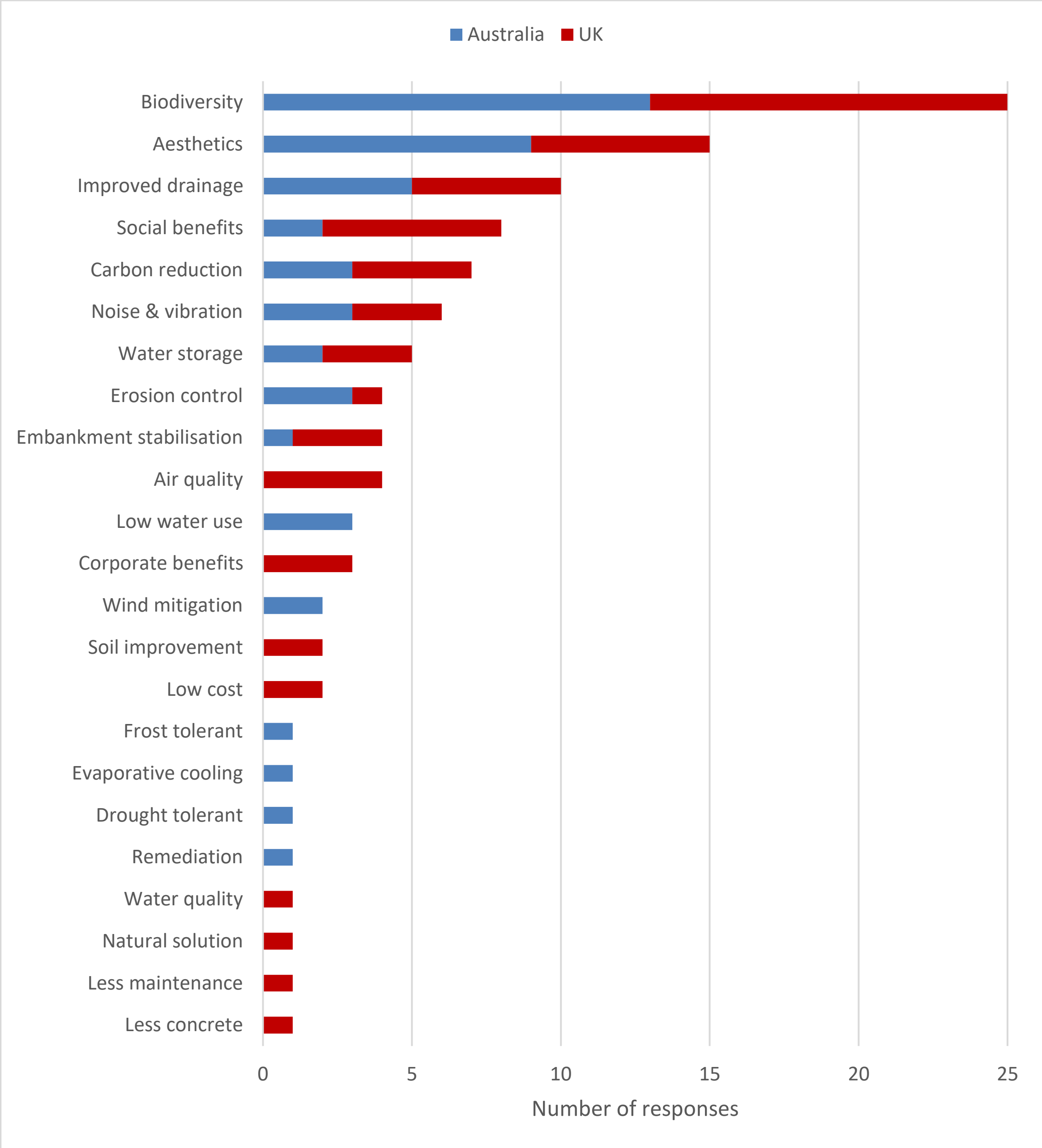


Figure 4-7 Additional benefits gained through NbS implementation

4.4 Implications for the rail industry

The implications of the outputs of this research to the rail industry are discussed below, and are considered in relation to the three RQs.

4.4.1 RQ1 Confirmed usage of NbS for CCA by the rail industry which is not included in the literature

Results from this survey are encouraging in that they confirm many examples of NbS being used to protect and adapt rail infrastructure in response to climate change, and that the rail industry is using the concept despite the extremely limited uptake suggested by the (lack of) literature on this topic. Because of the paucity of scientific or grey literature on the subject, however, there is limited promotion of the use of NbS as CCA for rail infrastructure, which may hinder its further uptake. This is confirmed by survey respondents citing a lack of awareness of the concept as being the biggest barrier to its uptake. Education of the rail industry on NbS is therefore a top priority. The further examination and documentation of the NbS examples cited in this research (where identifiable), and sharing of this information within the industry could assist with this.

4.4.2 RQ2 Rail industry barriers to the operationalisation of NbS as CCA measures

The understanding of constraints is crucial to identifying ways of successfully delivering CCA measures and identifying adaptation opportunities (Nalau et al., 2018). The challenges and barriers to the operationalisation of NbS as CCA measures for rail confirmed by RQ2 are valuable in this regard and should be addressed in the mechanisms adopted to roll out NbS in the industry; for example, rail standards and guidance for rail must address maintenance practices and requirements. Recognising the importance placed on the need for NbS education in the industry, training and awareness content should cover each of the constraints included in Table 4-2 and Figure 4-6; whilst sharing the many cited benefits of NbS (Table 4-3 and Figure 4-7), doing so will help to counter rail resistance to change, identified as a key barrier to uptake by 13.9% of survey participants.

The predetermined list from which survey participants could select their top perceived barriers to NbS uptake had been aligned with the seven barrier themes identified through literature review (Blackwood & Renaud, 2022). The spread of questionnaire responses received across all twelve listed barriers (as shown in Table 4-2) validates the literature review conclusions, whilst quantitative analysis of the survey responses provides a means of measuring the perceived significance of what had previously been only qualitative findings; for example, 'Lack of cost benefit analysis' is regarded by more rail professionals to be a barrier than 'Climate change uncertainty'; this data could therefore be used by the rail industry to prioritise NbS enabling measures (as per Table 4-3) to focus on the biggest apparent barriers first. Questionnaire responses on the problems encountered during NbS implementation (Figure 4-6) have provided more practical and logistical perspectives on barriers to the use of NbS in the rail environment than were possible to identify through literature review, due to the lack of literature on NbS being used in rail. Examples of the additional barriers this research has identified include difficulties in sourcing suitable plants, and security concerns due to the introduction of vegetation potentially contravening Crime Prevention Through Environmental Design strategies, which are important measures for reducing crime on public transport, particularly in and around railway stations (Cozens & van der Linde, 2015). It will therefore be important that enabling measures developed to support NbS roll out in rail address these barriers highlighted by the industry.

Further, regarding funding, the cost and lack of cost benefit analysis for NbS were cited as top barriers to their implementation by 7.9% and 10.9% of survey respondents, respectively, meaning that the financing of NbS is perceived as a challenge to their uptake by almost one fifth of participants. Expenditure would be required for a rail organisation to implement CCA of any type (grey or green). The greatest problem for the industry is likely to be at the point of planning CCA interventions due to uncertainty over how much NbS will cost over their lifecycle, and how this compares to traditional measures. NbS are disadvantaged by CCA decision-making being dependent on economic appraisal models customised to traditional, grey preferences (Chausson et al., 2020), and difficulties in forecasting or measuring the effectiveness of NbS mean that there can be high uncertainty over their cost-effectiveness relative to alternative options (Rizvi et al., 2015). In addition, Seddon et al. (2020) note how "inflexible and sectionalized forms of governance" mean that grey, engineered interventions remain default CCA options, thereby representing further hindrances to NbS uptake. This is likely to be the case for society in general, however, observation of this problem is expected to be amplified in the complex rail industry which involves multiple interconnected networks and stakeholders, whilst also being steeped in grey engineering traditions (Blackwood & Renaud, 2022). This augments the recommendation for the more gradual phasing-in of NbS to rail organisations through green-grey hybrid solutions (Blackwood & Renaud, 2022), which is supported by the growing consensus in the general roll out of NbS i.e., not specific to railways, that when comparing the costs and benefits of NbS against engineered approaches, hybrid solutions may present the best option in many contexts (Seddon et al., 2020b). The development of multi-criteria assessments which enable the costing and comparison of the multiple social, economic, and environmental co-benefits that can be derived from NbS is imperative to their universal roll out (Chausson et al., 2020; Frantzeskaki et al., 2019; Kabisch et al., 2016; Ruangpan et al., 2020). This does, however, present an opportunity for the rail sector to work with and learn from other industries to advance the tools and guidance to support the wholesale dissemination of NbS. In particular, railways could work with other transportation and linear corridor industries, such as highways and telecommunications, to develop shared solutions whereby collaborative approaches may also generate greater cumulative CCA benefits (Blackwood & Renaud, 2022).

4.4.3 RQ3 Rail industry aids to the operationalisation of NbS as CCA measures

Rail industry respondents in Australia and the UK agree that legislation, policy, standards and client specification will be the best mechanisms to support the wider implementation of NbS (Table 4-3). To develop these instruments, set requirements and provide guidance to the industry, initial education and awareness are likely to be required by the legislation, policy, standard and specification setting bodies in both countries; this further emphasises the importance of and need for education. These parties will also need access to sufficient examples and robust evidence of NbS concepts in use to inform their development of the material required to set rail industry direction and guidance. With the setting of legislation and standards comes the matter of compliance and adherence. Seddon et al. (2021) note that companies have historically failed to comply with voluntary environmental agreements, and therefore advocate rigorous assessment and validation through independent regulatory frameworks, supported by government policy. For the rail industry this would require clarification as to whether enforcement would sit with rail or environmental and planning regulators.

To provide the clear principles and evidence-based frameworks deemed necessary to aid NbS practitioners (Cohen-Shacham et al., 2019), standards for rail NbS will need to be based on tried and tested examples, particularly from a rail safety perspective (Blackwood & Renaud, 2022). The development of evidence-based criteria will not only support the design and implementation of NbS but also enable NbS commitments, relating to both climate change and biodiversity, to be monitored and improved with time (Seddon et al., 2021). The construction of the new HS2 infrastructure in the UK, including the multiple NbS examples that are part of its "Green Corridor online mapping tool" (H. S. Ltd, 2022), presents an excellent opportunity to trial NbS concepts from which the rail industry could learn and use to develop policy, standards and specifications. Findings from HS2 would only be relevant to the UK and its climate analogues (Sanderson et al., 2016), however any successful approaches and tools developed and/or lessons learned from site-specific case studies could be shared for application in the rail industry globally, for instance through dissemination by the International Union of Railways (UIC, 2022).

'Landowner partnerships' was the measure least regarded as being an enabler to widespread NbS uptake, attracting only 1.9% and 3% of responses in Australia and the UK respectively (Table 4-3). Such alliances, however, are likely to be instrumental in the successful implementation of NbS for rail for several reasons. Firstly, because the co-development of NbS with stakeholders, including landowners, is a key stage in the operationalisation of NbS (Kumar et al., 2020). This step is presented as an essential activity in the 'validation of NbS options for rail' phase of the framework to incorporate NbS as CCA measures for rail infrastructure proposed by Blackwood & Renaud (2022). The failure of the rail industry to co-develop with adjacent landowners could therefore equate to failure of the validation of NbS options for rail, leaving the concept unable to get off the ground in the industry. Additionally, co-development through collaborative research and coproduction between scientists, practitioners, and the community is promoted as a means of advancing the planning and knowledge agenda for NbS (Frantzeskaki et al., 2019). Involving stakeholders in joint 'Open Air Laboratories' (OALs) could also help to build a robust evidence base by demonstrating the effectiveness and sustainability outcomes of applying NbS compared to other CCA measures. For the rail industry, stakeholders should include lineside neighbours. These collaborative OALs could help to provide evidence to respond to questions or challenges raised regarding NbS performance uncertainty, lessen reluctance and cynicism in selecting natural solutions over engineered alternatives (Kabisch et al., 2017) whilst potentially overcoming railway engineers' path dependency on traditional grey solutions. Furthermore, the limited amount of land directly available to rail infrastructure owners, i.e., generally long but very narrow corridors, presents a significant constraint to NbS uptake at scale (Travers et al., 2021); this means that, without partnerships between rail and non-rail land owning neighbours, there may not be sufficient space to successfully implement NbS. The NbS concepts that survey participants had most awareness of and involvement with (natural drainage, green corridors and the use of vegetation to protect assets/infrastructure (Figure 4-2)) are generally localised solutions, which would be more practicable to implement within the confines of the land owned by railways. Survey responses may therefore reflect this spatial constraint, with the lower levels of awareness and application of concepts such as reefs, mangroves and dune/beach restoration being due to these solutions requiring land take out-with the area of control of rail infrastructure owners. Finally, the formation of landowner partnerships would be critical to the realisation of the multiple potential community and social sustainability opportunities that joined-up NbS interventions may deliver, as detailed in Figure 4-7.

The above points confirm that investigation into the formation of landowner partnerships represents a critical activity for the rail industry to undertake before embarking on the design, development and/or deployment of NbS. Use of the other enabling mechanisms listed in Table 4-3 (e.g., education on the benefits of co-development and the provision of funding or incentives for this) could therefore be required to instigate collaborative NbS partnerships between rail infrastructure owners and their lineside neighbours to ensure that this happens.

It has been observed that very few studies on the adaptation performance of NbS have considered broader social, climate change mitigation, or, in particular, biodiversity outcomes, which have received only very basic coverage (Chausson et al., 2020). The large number of global annual rail passengers (2.78 million passenger-km), lineside neighbours (along track lengths of 801,357 km), and rail industry employees (6 million) (International Union of Railways, 2022) put railways in a prime position to access and monitor social sustainability data, including, for example, the social benefits quoted in survey responses as presented in Figure

4-7: aesthetics ("pleasing and relaxing environment", "provision of shade, colour and aromas"); noise and vibration; air quality; social benefits; biodiversity ("access to nature"). This provides the rail industry with an excellent opportunity to lead the way in collating data and learnings on NbS performance, and stakeholders' perception of their performance, which may be shared universally, internal and external to the sector. The quantification of the additional benefits gained through NbS implementation, as identified by participants of this study and shown in Figure 4-7, would aid the promotion and subsequent operationalisation of NbS. Rail companies already undertake extensive vegetation surveys (for example, Network Rail, 2022b; Rail Safety and Standards Board Ltd., 2018; T. E. C. Associates, 2021) representing a vehicle for the ongoing performance monitoring of plants being employed as NbS. However, ecologists would have to be deployed, and/or in-house staff trained up with basic ecological identification skills, in order to assess the wider biodiversity status of NbS locations, e.g., to validate increases in wildlife and habitats. Recognising that biodiversity gain is only one of the multiple benefits recognised by survey participants (Figure 4-7), it is important that the multiple values of NbS, specifically the values of nature, are respected (Seddon, 2022). There is otherwise a danger that token NbS are implemented as a means of greenwashing (Anderson et al., 2019), with concerns already being raised that organisations are promoting their use of NbS whilst failing to take action to reduce fossil fuel consumption (Edwards, 2020), and high greenhouse gas emitting industries, including airports, are using NbS to offset their emissions (Seddon et al., 2021). Whilst rail is the least emissions-intensive mode of passenger transport (International Energy Agency, 2023), as well as taking steps to introduce sustainable CCA measures through use of NbS, the industry must continue in tandem to pursue means of reducing its emissions, e.g., through the electrification of diesel operations, to support global climate change mitigation effort.

4.5 Conclusion

There is a pressing need for railways to protect their infrastructure from and adapt it to accommodate the impacts of climate change. NbS have been recognised as potential CCA options for rail which may also deliver a range of additional ecosystem service benefits. To date, however, the widespread application of NbS by the rail industry has not been evident. Through engagement with international rail professionals, whilst limited by a relatively small sample size due the niche group of stakeholders that was targeted, this research has confirmed multiple examples of NbS in use in rail which are not included in the literature. The most commonly found NbS concept that is in use was natural drainage, which was predominately being applied in response to high precipitation events.

Many factors would have to be considered to support the widespread implementation of NbS in rail. This study has established that a lack of awareness of NbS is the largest perceived barrier to NbS uptake; education on and promotion of NbS in the industry will therefore be key to its successful deployment. Meanwhile, survey participants saw policy, standards, and client specification as the best vehicles to enable greater NbS uptake. To inform the development of these instruments, rail industry NbS case studies are recommended as a means of providing strong evidence and examples. OALs could be used to generate the required technical data whilst also offering live demonstration sites to educate stakeholders internal and external to the rail industry.

Encouragingly, this research has proven that rail professionals recognise the wide range of benefits that NbS can deliver in addition to their CCA function. This added value that natural solutions can provide, combined with evidence-based data and information that NbS can contribute effectively to CCA, should be used as an argument for the roll out of NbS as sustainable solutions for the rail industry, especially when making comparisons with traditional, engineered alternatives.

Chapter 5 A framework for the successful application of nature-based solutions for climate change adaptation on rail infrastructure developed through the examination of two case studies

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Abstract:

The management of railway infrastructure to withstand more frequent and more extreme weather conditions caused by climate change presents a significant global challenge for the rail industry. Nature-based solutions (NbS) have been proposed as potential options to protect and adapt rail infrastructure to accommodate the impacts of climate change, and an initial framework to aid the implementation of NbS in the industry has been developed. Few examples of the application of NbS in the rail environment have been documented however, with a lack of awareness on the concept being cited as the most significant barrier to its dissemination. By examining the application of NbS on two rail case studies in Adelaide, Australia, and Yorkshire, UK, including focus groups and interviews with rail professionals involved in each, this research explores the barriers encountered and the aids to NbS implementation used in these live railway examples, enabling the testing and refinement of the NbS operationalisation framework to produce an improved tool for use by the rail industry. The rail-specific case study outputs contribute to industry knowledge and awareness on NbS, which is critical for its successful uptake

on rail infrastructure for climate change adaptation, and will support the continued provision of safe, sustainable rail services.

Key words:

Nature-based Solutions; Rail infrastructure; Climate change adaptation; Green track; Vegetated culvert

5.1 Introduction

Nature-based solutions (NbS) have been positioned as potential 'green' alternatives or complements to 'grey' engineered (human-made, anthropogenic (Wesener & McWilliam, 2021)) climate change adaptation (CCA) measures on rail infrastructure (Blackwood & Renaud, 2022; Blackwood et al., 2022; Blackwood et al., 2023; Kostianaia & Kostianoy, 2023; Ribeiro et al., 2022). With the scale, frequency and duration of many extreme weather events that may threaten the safe operation of railways projected to increase with future climate change (Austin, 2023; IPCC, 2021, 2022), the need for the rail industry to protect its infrastructure from and adapt it to accommodate the effects of climate change is increasing rapidly. In addition to the CCA-specific ecosystem regulating services provided by NbS e.g., regulation of climate, water quantity and quality, erosion and other natural hazards (Millennium Ecosystem Assessment, 2005), the many further benefits that they can deliver, such as increasing biodiversity and aesthetical enjoyment, present NbS as an attractive option for railways to consider introducing, or restoring, in the rail environment (Blackwood & Renaud, 2022; Blackwood et al., 2022).

Encouragingly, rail infrastructure owner commitment to implementing NbS, including its usage for CCA purposes, has been observed, (e.g., Network Rail 2020b, 2022a). However, despite considerable research having been conducted on the implementation of NbS in urban settings (Bayulken et al., 2021; Kabisch et al., 2017; Sarabi et al., 2019), very few studies have explored their use in the rail context to date (Blackwood & Renaud, 2022; Blackwood et al., 2022). There is generally little literature on CCA of any type for the rail industry (United Nations Economic Commission for, 2020; Wang et al., 2020b), and very few recorded examples of NbS being used in rail exist (Blackwood & Renaud, 2022; Blackwood et al., 2022). As NbS is a relatively new concept, there may be examples of NbS being used in the rail environment (including green-grey 'hybrid' interventions) that do not feature in the literature due to them not being recognised or specifically labelled as NbS (Blackwood & Renaud, 2022; Blackwood et al., 2022). The very limited number of examples of NbS application in the rail context may also reflect several barriers that have been identified to their adoption, including safety concerns, time constraints and stakeholder dependencies, for instance (Blackwood & Renaud, 2022; Blackwood et al., 2023). Despite these hurdles, recognising the industry's need to urgently implement sustainable CCA measures, Blackwood et al. recommend potential NbS options as alternatives and/or complements to grey CCA options, in response to the range of hydro-meteorological hazards to which rail infrastructure is exposed (Blackwood et al., 2022), and a framework to aid the implementation of NbS as CCA for rail has been proposed (Blackwood & Renaud, 2022). Meanwhile, an international survey of rail professionals revealed multiple examples of NbS being used for CCA in rail which had not been included in the literature, with the study confirming the key perceived barrier to their implementation in the industry as being a lack of awareness of NbS (Blackwood et al., 2023). The provision of information on and the promotion of NbS within the rail industry are therefore critical to their successful roll out, and the sharing of rail-specific examples of NbS application is likely to aid their wider uptake by the sector (Blackwood et al., 2023).

To aid the operationalisation of NbS as CCA measures for the industry, this research explores the steps taken to integrate and manage NbS in two rail case studies: green track at Victoria Square in Adelaide, Australia ('VSA'), and a vegetated headwall on the Brumber Hill Culvert in Yorkshire, UK ('BHC'). An overview of the NbS in place at each location is provided, and the barriers and tools to their deployment are identified and compared with those suggested by Blackwood and Renaud, including those considered in the proposed 'Framework to incorporate NbS as CCA measures for rail infrastructure' (Blackwood & Renaud, 2022) ('Framework'), an abridged version of which is shown in Figure 5-1. The research questions and objectives shown in Table 5-1 are used to focus the case study research.

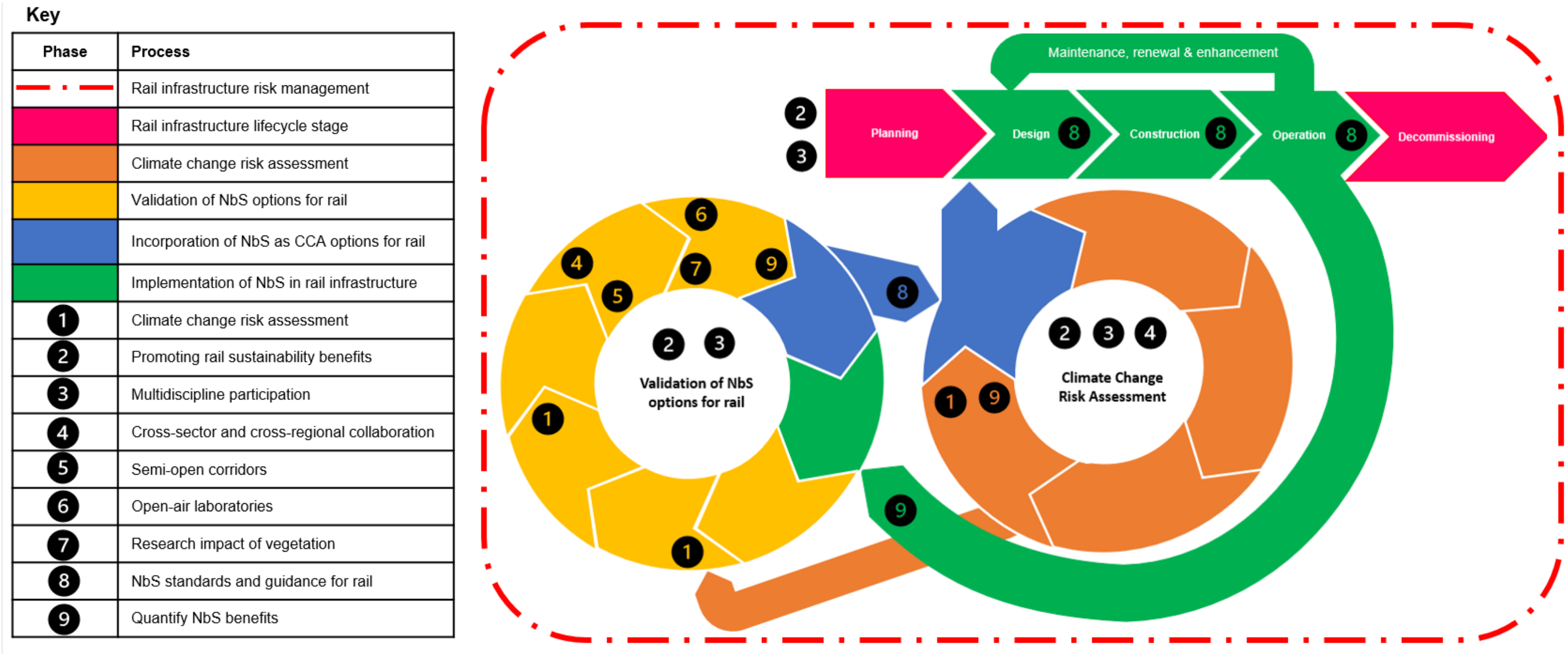

Figure 5-1 Framework to incorporate NbS as CCA measures for rail infrastructure

(Adapted from Blackwood & Renaud, 2022)

Table 5-1 Research questions and objectives

Research question (RQ)	Research objective (RO)
RQ1: What are the challenges and barriers to the operationalisation of NbS as CCA measures for the rail industry?	**RO1:** Identify barriers and challenges encountered in the implementation of NbS at BHC and VSA, including any additional barriers to those identified in the literature, and through engagement with rail industry professionals (Blackwood et al., 2023).
RQ2: What could aid the operationalisation of NbS as CCA measures for the rail industry?	**RO2:** Identify aids to the implementation of NbS as CCA measures at BHC and VSA, including additional aids to those identified in the literature, and through engagement with rail industry professionals (Blackwood et al., 2023).
	RO3: Refine the 'Framework to incorporate NbS as CCA measures for rail infrastructure' (Blackwood & Renaud, 2022) using learning from BHC and VSA, to provide an improved framework for use by the rail industry.
	RO4: Contribute to education and knowledge on NbS use in rail for CCA by preparing two rail-specific case study examples.

5.2 Study Sites

5.2.1 Green track at Victoria Square, Adelaide, Australia

Located in the central business district of South Australia's (SA) state capital, Victoria Square is a "formal and dignified" public space which hosts a range of civic, cultural, sporting and recreational activities, and is served by public transport (Government of South Australia, 2006a, p. 7) including Adelaide Metro tram ('light rail') services (South Australia Government, 2023). The 2007 extension of the Glenelg tramline saw the construction of a tram track and new stop in VSA, with 180 metres of the new line (1475m^2) being laid with a grass 'green track' (Figure 5-2 Green track at Victoria Square, Adelaide), as opposed to the concrete paving used elsewhere on the tram corridor (Government of South Australia, 2006a, 2006b). Green track is a vegetative layer comprising of grasses (most common), turf or groundcovers, planted between railway track beds. The track beds can be installed using roll-out turf or self-seeding grasses, with examples being found in many European cities (Pfautsch & Howe, 2018).

Figure 5-2 Green track at Victoria Square, Adelaide

Photo: L. Blackwood, 2023

Green track usually requires maintenance including irrigation, mowing and weeding. Benefits of using a ‘green’, NbS, over ‘grey’, concrete or ballasted, track bed alternatives include noise reduction (Pfautsch & Howe, 2018), aesthetic improvement, and better public acceptance of tram schemes and their operators (Kraus et al., n.d.; Pfautsch & Howe, 2018; Schreiter & Kappis, n.d.). Further ecosystem services provided by green track include carbon sequestration, the absorption and retention of pollutants, and an increase in biodiversity, whilst presenting a less carbon-intense option (Monteiro, 2017). Finally, from the CCA perspective upon which this research is focussed, green track can moderate urban temperature extremes, and reduce run-off and erosion (Monteiro, 2017; Pfautsch & Howe, 2018; Schreiter & Kappis, n.d.). Green track, presenting both ‘green corridor’ and ‘natural drainage’ solutions, has therefore been proposed as a potential NbS alternative and/or complement to grey CCA measures for the rail industry to use in response to high and low temperatures and high precipitation (Blackwood et al., 2022); these extremes can be exacerbated in inner city environments, such as central Adelaide, where sealed surfaces create urban heat islands and high storm water run-off events (Schreiter & Kappis, n.d.).

The grass used on the green track has remained well established since its planting in 2007 (Pfautsch & Howe, 2018), presenting VSA as an operational example of NbS in use on light rail infrastructure. The differing track engineering specifications between conventional 'heavy' and 'light' rail (tram) infrastructure mean that green track is not suitable for heavy rail infrastructure (Blackwood et al., 2022); however, learning from the implementation of an NbS concept on light rail remains relevant and transferable to the consideration of applying NbS on conventional railways.

5.2.2 Vegetated culvert headwall at Brumber Hill, Yorkshire, UK

'Flex MSE®' was installed to repair a culvert headwall structure at Brumber Hill, Yorkshire, in 2021 as part of the Transpennine Route Upgrade (TRU) railway improvement programme (Transpennine Route Upgrade, 2023a) (Figure 5-3 Vegetated culvert headwall adjacent to railway at Brumber Hill, Yorkshire). Flex MSE ® (Mechanically Stabilised Earth) is a patented engineered system consisting of geotextile bags and engineered plates that can be used to create modular retaining walls and erosion control, and allow the integration of vegetation. This example of a green/grey hybrid CCA solution has used bioengineering and water sensitive urban drainage (WSUD) NbS concepts (Blackwood et al., 2022) to provide a strengthened headwall and increased drainage capacity to protect the culvert from, and allow it to accommodate, the increase in precipitation and flood events projected with climate change. Whilst the headwall is not on railway-owned land, the culvert conveys railway drainage, and the reinforced structure therefore protects the upstream rail infrastructure and rail services. Following its successful application at BHC, as examined in this study, the product is being designed into further railway culverts and gravity wall systems (Rail Director, 2022).

Figure 5-3 Vegetated culvert headwall adjacent to railway at Brumber Hill, Yorkshire
Photo: Scott Parnell Ltd. (2022), reprinted with permission

5.3 Methods

Case study research was applied to explore the implementation of NbS for CCA in rail using BHC and VSA as specific examples. The two locations were selected based upon the accessibility to information and willing research participants for each case, whilst avoiding conflict of interest for the author. The research was based on: archival records, organisational documents, direct observations (of VSA only), focus groups and interviews. These multiple sources were used to confirm the processes followed to implement NbS over the lifecycles of rail infrastructure on both assets, the combination of approaches capturing a breadth of information and enabling the triangulation of key findings. These processes were reviewed against those in the Framework (Blackwood & Renaud, 2022), with each case being considered in the chronological order of the rail infrastructure management lifecycle detailed therein (Planning; Design; Construction; Operation; Maintenance, renewal and enhancement). Whilst the Decommissioning lifecycle stage is included in the Framework, this phase was not considered during the focus groups or interviews due to the long asset life remaining for each case and neither yet having a proposed decommissioning date; additional uncertainty over the future stakeholders who would be involved at the end of the infrastructure lifecycle made it impossible to identify the relevant parties to invite to participate. The observations made relating to, and refinements made to the framework regarding, the Decommissioning phase are therefore based on applicable learning gained on earlier lifecycle stages, and from literature on the decommissioning of rail infrastructure and NbS.

Noting the limited number of examples of NbS being used for CCA in rail identified in the literature from which to be able to select suitable cases (Blackwood et al., 2022; Blackwood et al., 2023), and research time and resource limitations, conducting two studies provides the opportunity to perform in-depth comparisons on the appropriateness of the Framework for two locations with different contexts, climates and rail infrastructure ages. This approach will strengthen arguments on the generalisability and operationalisation of the Framework, with conclusions drawn from two cases being stronger than those arising from an individual case (Yin, 2018).

To supplement the information on challenges and aids to NbS implementation identified via the documentation available and observations undertaken for each case, focus groups and interviews were held with purposively sampled stakeholders involved in the design, operation and maintenance of both examples, the planning of BHC, and stakeholders who would be involved in the planning phase of future rail infrastructure in VSA. Direct communication with purposively selected individuals who had first-hand knowledge and experience of each case maximised the opportunity to obtain high quality information pertinent to the RQs (Creswell & Plano Clark, 2018). Targeted invitations and requests to participate were distributed via two gatekeepers, one representing each case. Ethical clearance for data collection was granted by a dedicated panel at the University of Glasgow, College of Social Sciences. All responses were voluntary and treated anonymously. Whilst data, including job titles, have been anonymised through coding, due to the small number of research participants and publicly accessible information on stakeholders involved in each case, all participants were advised that their anonymity may not be guaranteed (this includes gatekeeper knowledge of potential participants, and their deductive disclosure from individual's responses). Informed consent to proceed on this basis was obtained from all participants prior to commencing the focus groups and interviews.

The focus groups involved two or three participants per session (VSA comprised two focus groups, each with three participants, and one interviewee; for BHC there was one focus group with two participants and two individual interviewees); this enabled a balance between depth of insight and volume of transcribable data. A semi-structured interview format was used to collect participants' observations, perceptions and attitudes on the implementation of NbS. To help focus research outputs, the question set was aligned with the RQs and ROs in Table 5-1. To avoid influencing participants' responses, general feedback was requested on the NbS in each case before presenting 'poll' slides containing lists from which participants could select their top perceived barriers and tools to NbS implementation. Use of semi-structured interviews enabled the collection of qualitative data targeted to the research questions, whilst allowing participants to express themselves freely. This format provided an opportunity to identify additional actions and tools that may be used to counter further barriers to NbS implementation, identified through RQ2, which are not already included in the literature. Whilst this research involved small sample sizes, reflective of the purposive sampling employed, the in-depth responses provided by participants, and subsequent verification of interview and focus group findings, combined with the other data sources used, enabled saturation to be reached (Creswell & Plano Clark, 2018). The interview question set, as shown in **Supplementary Information 1 (SI 1**) [Appendix C], was pre-tested through distribution to two rail industry professionals.

Interview and focus group sessions were recorded and manually transcribed. Individuals are referenced by their case and focus group or interview number (e.g., VSA G1P1 = VSA Group 1, Participant 1, BHC I1 = BHC Interviewee 1).

5.4 Results and discussion

The barriers and aids to NbS implementation observed for each case are detailed below (in response to RO1 and 2 respectively), in chronological order of when they were encountered during the rail infrastructure lifecycle. A concise summary of these comprehensive findings, including key learning from the analysis of the implementation of NbS in both cases and interviewee and focus group feedback on the appropriateness of the Framework, is presented in Table 5-2. These conclusions are presented in Table 5-3 which describes the refinements that have been made to develop the final version of the Framework, Figure 5.4, which has been prepared to fulfil RO3.

The rail-specific publications developed to achieve RO 4 are presented in SI 2 and SI 3 [Appendices D and E].

5.4.1 Green track installation at Victoria Square, Adelaide

5.4.1.1 VSA Planning

The green track was installed as part of the 2007 Glenelg Tramline Extension (GTE). The proclamation of the Victoria Square Act 2005, during the GTE project's planning phase, supported the sustainable development of the tramline in Victoria Square by designating certain land as 'parkland' (Parliament of South Australia, 2005) or 'community land', i.e., for the benefit and enjoyment of the community (Parliament of South Australia, 1999). The GTE planning Development Application (DA) (Government of South Australia, 2006a), approved in 2006, subsequently committed to laying grass to complement and integrate into the local environment as much as possible (Collis, 2007; Government of South Australia, 2006a, 2006b), and stated that the development would improve the pedestrian environment by providing a "visually attractive and interesting addition" to the city's street functions (Government of South Australia, 2006a, p.20).

The environmental and social impacts considered during the planning phase (vegetation, storm water management, noise, vibration and air quality impacts) did not consider the potential positive ecosystem services, nor the disservices, that could be introduced through the use of green track (Government of South Australia, 2006a). The GTE preceded the introduction of the need for relevant projects to undertake a planning phase Environmental Impact Assessment (EIA) which identifies and addresses the effects of developments on climate, and the measures proposed to mitigate or address these, as is now required in SA by the Planning, Development and Infrastructure Act 2016 (Government of South Australia, 2016). Planning decisions made under the Act must now also reflect SA's State Planning Policy 5: Climate Change ('SPP 5'), which specifies the principles to be applied to relevant developments with respect to minimising adverse effects on the climate, and promoting climate change resilience (Government of South Australia, 2016, 2019b). The Regulations that sit under the 2016 Act restrict the applicability of the legislation to certain lengths of track, i.e., over 1km of new track (Government of South Australia, 2017b) which, from a CCA and subsequent NbS roll out perspective, unfortunately inhibits the mandatory climate change consideration on shorter, exempt, track. Additional SA SPPs which further support the implementation of NbS for CCA include those relating to Biodiversity (SPP 4), Climate Change (SPP 5), Strategic Transport Infrastructure (SPP 11) and Natural Hazards (SPP15) (Government of South Australia, 2019b). These SPPs advocate sustainable development through the application of WSUD and green infrastructure (GI) to minimise the risk to people, property and the environment from exposure to natural hazards including extreme weather events, taking the impacts of climate change into account. Furthermore, multiple SPPs encourage the development and promotion of public transport as a sustainable transport mode, which is cited as an important action to aid the successful implementation of the Framework (Blackwood & Renaud, 2022).

Whilst not in existence during the planning phase of the GTE project in 2006, the SA planning framework now in place means that the implementation of NbS for CCA in rail infrastructure schemes would be aided through current planning legislation and SPPs which require the assessment of climate change impacts, and reference and promote the use of NbS concepts to applicable rail infrastructure. The SA Government's advocacy of the implementation of NbS is further confirmed through their 'Green Infrastructure Commitment' which states that, when planning transport infrastructure projects, their Department for Infrastructure and Transport (DIT) will account for the space required to implement WSUD, an NbS concept which has been recommended for application in rail (Blackwood et al., 2022), and factor this into land purchasing decisions (Government of South Australia, 2021c). This measure helps to counter the land use constraint identified by Blackwood & Renaud (2022). Furthermore, and of particular relevance to developments in urban Adelaide where VSA is located, the ‘Green Adelaide Regional Landscape Plan’ is presented as a “pathway to a cooler, greener, wilder and climate-resilient Adelaide” (Government of South Australia, 2021b, p. i), with a key focus being to aid and incentivise best practice WSUD in major transport corridors. VSA G1P1 advised of the DIT’s requirement for climate change risk assessments (CCRA) to be completed in the planning (and subsequent design) of new assets; they had not been involved in undertaking a CCRA, but were aware of a CCRA guidance document (Government of South Australia, 2021a) that is referenced in the DIT’s Sustainability Manual (Department for Infrastructure Transport, 2022) and Master Specification for Planning Investigations (Government of South Australia, 2022), which each specify the need to conduct CCRA and to assess opportunities to incorporate GI into the asset(s) being planned. Specific to rail infrastructure, the Master Specification for Railways Management Planning does not explicitly reference the need to conduct a CCRA; however, it does require contractors to comply with DIT Risk Management specifications, which encompass CCRA (Government of South Australia, 2019a). This specification therefore provides a tool to encourage CCRA and the subsequent potential uptake of NbS in future rail infrastructure developments.

VSA G1P1 cited a DIT rail project – the Port Dock Railway Line – that they are aware is currently going through planning consultation (Government of South Australia, 2023a). Whilst the upgrade and extension of the railway infrastructure (‘heavy’ rail, not ‘light’ as per the GTE) do not fall under the requirements of the Planning Regulations (Government of South Australia, 2017b), a CCRA has been undertaken which identified high-level adaptation recommendations for the project design. The measures incorporated include WSUD using detention basins and sustainable drainage infrastructure to protect and/or improve water quality, the use of GI in response to increased average annual temperatures, decreased average annual rainfall, increased rainfall intensity, more extreme temperature days, sea level rise and increased storm surges (Department of Planning Transport & Infrastructure, 2019), and the intent to improve biodiversity, with self-sustaining vegetation being selected to avoid excessive irrigation or frequent replanting (Department of Planning Transport & Infrastructure, 2019). The Port Dock Railway Line project therefore provides an encouraging example of NbS being included as CCA for rail infrastructure during the project planning phase; the proposed uptake of NbS has clearly been facilitated by legislation and government policy. The use of such tools to enable the widespread uptake of NbS as CCA options for rail was echoed by industry professionals who cited 'Policy and Standards' as being the top vehicle with which to support NbS deployment (Blackwood et al., 2023).

As well as predating the introduction of now applicable legislation, the planning phase of the GTE also precedes key milestones in the emergence of the NbS concept, such as the 2008 publication of the World Bank Report 'Biodiversity, Climate Change and Adaptation: Nature-Based Solutions from the World Bank Portfolio' (The World Bank, 2008), and the surge in NbS research, predominantly in Europe, from 2015 to the present (Cohen-Shacham et al., 2016). Although those involved in the planning of the GTE may have acknowledged the wider benefits of using green track, potentially due to the lack of literature (and general awareness) on NbS in 2006, combined with there being no formal requirement to consider CCA at that time, the use of green track at VSA is documented as being solely for aesthetic purposes (Government of South Australia, 2006a). It therefore appears that the use of green track was planned only for sections of the tramline passing through VSA to visually integrate into the surrounding parkland (Collis, 2007), and it was not considered for use on the remainder of the 1.62km track extension, nor has any thought appeared to have been given to retrospectively installing green track on the 10.8km of existing tramline. Recognition during the planning phase of the full range of ecosystem services that green track can deliver may have led to more widespread incorporation of the concept into the GTE; this highlights the importance of assessing the full range of benefits from NbS utilisation and considering these during decision making processes in infrastructure development (Seddon et al., 2020a) (Table 5-2: Learning from both cases).

5.4.2 VSA Design

The GTE Urban Design Report provides concept illustrations and descriptions of the proposed tramline extension, including the green track at VSA (Government of South Australia, 2006b). Victoria Square is a fully 'open corridor', as tramlines are generally not fenced off, with this design approach being recognised as an aid to NbS deployment (Blackwood & Renaud, 2022). As required by the planning DA commitments (Government of South Australia, 2006a), the Design Report confirms that many features of the tramline extension were intentionally designed to be in keeping with the existing townscape and character of the areas it passes through. In this instance, the existing parkland at VSA presented an aid to the inclusion of NbS in the tramline design, which makes the landscape surrounding the rail infrastructure (current and/or future planned) an influencing factor when designing CCA measures and deciding whether these should include NbS. For example, if there is already vegetation in place, it could be viewed that additional vegetation (i.e., NbS) would be superfluous, representing a barrier to NbS uptake; meanwhile, in a built-up, urban area the re/design of railway infrastructure could be seen as an opportunity to increase biodiversity in the landscape, aiding NbS implementation; or, it could be viewed that grey infrastructure would be in keeping with the existing environment, impeding NbS use. Green track was integrated into the track engineering design to reflect the site-specific context of Victoria Square, namely its social and cultural context, whilst contributing to the parkland of the wider landscape. The VSA case therefore fulfils International Union for Conservation of Nature NbS Principles (Cohen-Shacham et al., 2016) and Global Standard criteria (IUCN, 2020) to design NbS relevant to geographic, economic and social scales, at and beyond the scope of the immediate intervention, with the aim of upscaling the NbS response where practicable. Although unintentional at the time of its design, VSA's alignment with these best practice standards reinforces the merits of sharing learning from the implementation of NbS at this location as a case study with the rail industry, and highlights value of international standards in propelling NbS uptake.

The inclusion of urban design elements in the GTE was limited by the track layout and positioning of special track features (e.g., turnouts and switches) (Government of South Australia, 2006a); this represents one rationale as to why green track was installed on some, but not all, of the tramline in VSA, and aligns with the 'Land use constraint' barrier to NbS implementation (Blackwood & Renaud, 2022), which is thought to be exacerbated in urban environments. The GTE Principal Designer describes the challenge of delivering the project within a highly urbanised setting which required the balancing of, often competing, technical and stakeholder limitations (Collis, 2007) (Table 5-2: Barrier - VSA).

Strong landowner partnerships and co-development, identified as activities critical to the successful roll out of NbS as CCA (Blackwood et al., 2023), are evidenced at VSA through the collaboration between the Designer and tramline landowner (City of Adelaide [CoA], who also own and maintain the land adjacent to the tramline in VSA) to co-develop the track design. This included, for example, the grass species selection (Kikuyu grass, *Cenchrus clandestinus*) already used by CoA and trusted as a "robust, resilient species that performs well in Adelaide climate" [VSA I1]. With CoA inheriting the maintenance of the green track post GTE construction, their involvement in the Design process aided the handover of the asset for its ongoing upkeep, and due to their prior experience of maintaining vegetation on the land adjacent, provided the assurance that the Maintainer would be able to manage the additional areas of grass (Table 5-2: Aid - VSA). Multidisciplinary participation in the NbS design, a recommended approach to aid NbS implementation (Blackwood & Renaud, 2022), has also been confirmed for the VSA green track through the observed involvement of urban designers, rail engineers and horticulturalists; this case also highlights the merits of involving stakeholders from multiple rail infrastructure lifecycle phases so that input and feedback can be obtained throughout the Framework process, e.g., by rail operators and infrastructure maintainers feeding issues, concerns and suggestions into the design of new infrastructure based upon their experiences of operating and maintaining existing assets. As it may not always be possible for individuals to input to design sessions in person, a process should be developed to record and share NbS and CCA performance data at and between all rail infrastructure lifecycle stages for reference by relevant parties involved in other phases; this should be accessible to other rail stakeholders who can utilise this data in CCA decision making and NbS planning and design (Table 5-2: Learning from both cases). A focus group participant noted that the Infrastructure Sustainability Council's (ISC) ratings scheme (Infrastructure Sustainability Council, 2021b), which is often mandated for use in the design of infrastructure projects, including rail, awards points for the inclusion of multidisciplinary participants in infrastructure design and associated CCRA [VSA G1P3]. This process, and the wider application of the ISC rating scheme which encourages and rewards the use of NbS including WSUD and GI (Infrastructure Sustainability Council, 2021a), therefore provides incentives for designers (from multiple disciplines) to incorporate NbS as CCA measures.

Whilst a relatively small-scale NbS installation, the complementary track design solution co-developed for the VSA green track helps to maximise ecosystem service delivery, including CCA, at the local landscape scale, which is a recognised aid to NbS implementation for rail (Blackwood & Renaud, 2022). However, the use of a single grass species represents a vulnerability to plant disease or potential die-off due to climate change induced impacts on growth; this ecosystem disservice is noted as a potential barrier to NbS uptake (Blackwood & Renaud, 2022). Care must also be taken to avoid the introduction of invasive species which can outcompete native vegetation, threatening local ecosystems and minimising potential biodiversity gains (Kabisch et al., 2016; Travers et al., 2021). Any future planned or required change to the green track's grass species would likely align with or be part of the redesign of the VSA parkland surrounding the tramline, and it is therefore thought that CoA would be involved in any redesign of the green track [VSA G2P1]. Research into worldwide green track utilisation was used to collate selection criteria to aid the choice of plant species to be used on the new Parramatta Light Rail green track in Sydney, Australia (Pfautsch & Howe, 2018). This list, which includes factors such as growth height and width, climate zone appropriateness, soil moisture requirements and weed suppression, could be used to inform the selection of any replacement vegetation required at VSA, and on this basis it is recommended that the selection checklist be utilised in the refined NbS Framework (Table 5-2: Learning from both cases). Given the prominence of the location and proactive maintenance regime in place for VSA, it is believed that any species decline, and selection of a suitable replacement would be well managed [VSA G2P1, P2]. The VSA case demonstrates that for high profile and publicly visible locations the aesthetical value of NbS could be a particular selling point for their implementation.

There is no evidence of the consideration of CCA or a CCRA being undertaken during the Design of the GTE, as recommended by the Framework, to identify the need for, or influence the selection of, CCA measures. This is most likely due to the timing of the GTE Design pre-dating the SA CCA legislation, policies and commitments that have been launched post GTE construction. The VSA green track was not designed with CCA specifically in mind, with aesthetics being the main driver (Government of South Australia, 2006a), although the integration of a NbS has clearly been a positive intervention. Whilst the policy's name suggests that it may warrant consideration only at the planning phase, SPP 5 prompts the need to understand climate change risks, and plan and design for these accordingly (Government of South Australia, 2019b). This means that the planning phase NbS implementation aid extends to a projects design stage, and warrants the movement of the CCRA process with the Framework, currently recommended to take place at design, being undertaken at the earlier planning stage; doing so may enable the siting of new rail infrastructure, decided in the planning phase, to be placed at an optimal location to avoid (or reduce) climate change impact on the asset, i.e., using the 'retreat' adaptation approach to avoid or lessen the extent of 'protect' or 'accommodate' CCA interventions required (Blackwood et al., 2023; Eichhorst, 2009) (Table 5-2: Learning from both cases). Research participants regard planning DA conditions of approval as being the strongest mechanism to "lock in" requirements, including those pertaining to CCA, for new and modified infrastructure design [VSA G1 P1, P2], as aligned with rail industry professionals' perspectives (Blackwood et al., 2023). A further design phase tool to establish compliance conditions for NbS being used as CCA exists through the SA Government's Green Infrastructure Commitment which sets WSUD performance targets in storm water design specifications for future rail (and other transport infrastructure) projects (Government of South Australia, 2021c), representing a strong vehicle to promote the use of NbS.

Focus group discussions on the technical requirements of designs saw one participant cite Adelaide's 'Cool Roads' study that tested the heat reduction ability of 'cool' (heat reflective) road sealants [VSA G1P2]. The sealants all showed a temperature reduction compared to an asphalt control road, with the study suggesting that cool road products might be preferable to street trees and GI, which can be challenging to plant and maintain in an urban environment, and can take significant time to establish (Marchant et al., 2020). Whilst this example relates to roads rather than rail, the study demonstrates the technological advances being made with construction materials which may present grey options as quicker, easier, and potentially more robust solutions which do not exhibit ecosystem disservices; this mindset may impact design phase considerations and mean a barrier to NbS uptake (Table 5-2 – Barrier: VSA). The discussion on the Cool Roads study reinforced the value of cross-sector collaboration between rail and roads, plus other industries, in the sharing of information on CCA and potentially to co-develop solutions, including NbS (Blackwood & Renaud, 2022). As a further example, a focus group participant described a linear reserve featuring GI successfully installed in the Adelaide suburb of Unley as a local 'best practice' illustration from which lessons could be learned and shared [VSA G1P3] (Government of South Australia, 2017a). Encouragingly, the Unley example was installed with the vision of providing a native plant corridor, an exercise pathway, a commuter corridor and peaceful park environment (Government of South Australia, 2017a), i.e., it showcases ecosystem benefits of natural solutions beyond the aesthetics-only consideration that was documented for VSA. The Cool Roads study used thermal imaging and temperature modelling software to obtain empirical data to compare products; this represents an important step that would be required to quantify and validate NbS performance, including their ecosystem services and disservices, enabling NbS to be compared to grey alternatives during design phase decision making and cost benefit analyses (CBA). There are not known to have been any measurements of CCA performance criteria, such as surface temperature or drainage performance, to enable a comparison between the green and traditional concrete-bedded track at VSA. Such an exercise would help to provide evidence on the effectiveness of the green track, and if favourable results were to be obtained for the NbS, could be used to promote wider roll out of the concept (Table 5-2: Learning from both cases).

5.4.3 VSA Construction

No construction phase constraints were identified in GTE literature nor provided by research participants, noting that the project was completed in 2007 and the construction company who delivered the works was acquired by another organisation in 2017, making it difficult to trace individuals who were directly involved in this phase. As the Framework involves the connection of, and communication of information between, rail infrastructure lifecycle stages, the lack of construction data available for the VSA case emphasises the importance of recording and sharing information on CCA and NbS between phases, and making this available to other rail stakeholders, reiterating the value of adding this key activity in the refined Framework (Table 5-2: Learning from both cases).

The Kikuyu grass used for the green track at VSA was delivered to site on pallets as turf (Halo, 2007), providing an immediate solution. Although it may take a short time for the turf to fully establish its root system, and subject to supply chain availability of the required vegetation, the ease of delivery of a pre-grown solution, avoiding the time required for in-situ growth, negates the perceived barriers of the potential time constraints of NbS (Blackwood & Renaud, 2022; Blackwood et al., 2023) and presents their supply in this format favourably (Table 5-2: Learning from both cases). Consideration of the supply and installation of any new or replacement NbS, including the location of and timescales for vegetation growth, would have to be given to any future grass replacement, for example if climatic change impacts grass growth performance, meaning that a different species is required to be planted (Table 5-2: Learning from both cases).

5.4.4 VSA Operation

Since the laying of the VSA green track and commencement of tram services on the extended tramline in 2007, there have been no growth performance issues reported with the Kikuyu grass. It has been observed to be in good health with continuous growth and no weeds spotted, and no turf replacement has been required (Pfautsch & Howe, 2018) [VSA I1]. Despite being viewed as the top additional benefit observed by rail professionals who have implemented NbS as CCA measures on rail infrastructure (Blackwood et al., 2023), there is not believed to have been any additional biodiversity recorded at VSA following the green track installation, nor have there been any sightings of species of note [VSA I1, VSA G2P1], with the highly urbanised setting and deliberate use of only one grass species presenting limited potential for biodiversity gain.

There have been no operational (tram service level or safety) problems caused to the tram operator or members of the public due to the use of green track at VSA [VSA G2 P1,2,3]. This feedback is contrary to operational risk being reported as the second largest problem encountered by rail professionals who have been involved in or aware of the implementation of NbS on rail infrastructure (Blackwood et al., 2023). The grass NbS in place at VSA does not present a significant operational hazard, however, as it is likely to be worn down by frequent tram services operating seven days per week (Adelaine Metro, 2021), combined with regular maintenance, making it unlikely to cause a sudden, catastrophic risk to a tram, as could occur with a treefall, for example. The lack of operational issues posed by the VSA green track positions the concept as an attractive option to roll out elsewhere on the Adelaide tram network, especially now that there is more awareness of the ecosystem service benefits delivered by the NbS; however, the expense incurred and disruption that could be caused to retrospectively install grass track means it is regarded as not reasonably practicable to do so [VSA G2 P1,2,3]. One focus group participant raised that, whilst green track may not be retrofitted onto the existing tramline route, they believe this would be likely for any new section of track being constructed, noting that green track has been installed into the new Parramatta Light Rail in Sydney (New South Wales Government, 2023) and is planned for the extension to Canberra Light Rail (Australian Capital Territory Government, 2023) [VSA G2P1].

Open-air laboratories (OAL) and the sharing of rail-specific case studies are recommended activities to support the implementation of NbS as CCA for rail (Blackwood & Renaud, 2022). With the VSA green track having been successfully implemented for over 15 years, this case provides a tried and tested OAL from which others can learn; the outputs from this research also provide further tools to communicate and promote NbS concepts in rail. Sharing the outcomes of other examples of NbS being used as CCA – both the successes and lessons for improvement learned – across the rail industry and other sectors, will remain an important action to aid the dissemination of the concept.

5.4.5 VSA Maintenance

The grass on the track at VSA is maintained by the CoA Horticulture Team, whilst the rail infrastructure manager (a body corporate, which is also the tram operator) is responsible for the maintenance of the rail track and associated infrastructure for the Adelaide Metro tram network. The relationship between these parties is managed through an Interface Agreement that clearly outlines roles, responsibilities and interface boundaries, including those for risk management, between tram track maintenance, tram operations and green track maintenance (Government of South Australia Rail Commissioner, 2019). Necessitated by rail safety legislation due to the inherent safety hazards associated with multiple parties carrying out activities in and near a live railway environment (Government of South Australia, 2012), the Interface Agreement confirms the relationships and communication channels between the multiple stakeholders involved in the operation and maintenance of the tramline, providing a formal vehicle to enable multi-discipline participation, a recommended activity to support NbS as CCA in rail (Blackwood & Renaud, 2022) (Table 5-2: Aid - VSA).

To fulfil the requirements of the Interface Agreement, CoA have undertaken a Health, Safety and Environmental Risk Assessment to identify the risks associated with, and controls required for, working adjacent to live rail traffic (City of Adelaide, 2019); these are documented and communicated to CoA employees via a Safe Operating Procedure (City of Adelaide, 2018). To avoid workforce exposure to tram movements, maintenance of the grass is scheduled to take place when trams are not operating, generally between 2-6am on Sunday mornings, with a 3-weekly schedule of approximately 2.5 hours per visit (Pfautsch & Howe, 2018) [VSA I1]. This constraint causes environmental nuisance due to night-time noise and lighting required to undertake mowing, brush cutting and leaf blowing [VSA I1]. Nuisance associated with the maintenance of vegetation on and near rail infrastructure therefore represents an ecosystem disservice of NbS (which should be accounted for in CBA undertaken to select CCA options), and a potential barrier to its uptake, particularly in highly residential areas at night-time, but also near sensitive receptors such as medical facilities and places of worship at any time of day (Table 5-2: Barrier - VSA).

The CoA grass maintenance team are professional horticulturists who have plant and machinery competences and have undertaken Rail Industry Worker (Australian Railway Association, n.d.) training to be able to work safely in the rail traffic environment [VSA I1] (Table 5-2: Barrier - VSA). No specific maintenance information was provided to CoA upon handover from the construction contractor; this has not been deemed a problem, however, as the horticultural team have extensive experience of managing vegetation, and their involvement in the GTE design meant that there was already familiarity with and experience of managing the Kikuyu species, aiding the handover process [VSA I1] (Table 5-2: Aid - VSA). The team have developed their own guidelines for the management of the turf, a key recommended tool to aid the implementation of NbS as CCA for rail (Blackwood & Renaud, 2022); the practices developed by CoA could therefore be shared with other NbS maintainers to help establish their own vegetation management procedures, the Adelaide-specific context of the guidelines being especially useful to climate and railway analogues (Sanderson et al., 2016).

The VSA green track is irrigated twice weekly for one hour using a sub-surface drip line system (Collis, 2007; Pfautsch & Howe, 2018), [VSA I1]. This has been claimed to generate high water demands (Pfautsch & Howe, 2018); however, CoA have unrestricted access to recycled water [VSA I1], thus reducing potable water demand. The grass is treated with 'Broadleaf Selective' herbicide and 'Blade Runner' fertiliser [VSA I1]. Whilst supporting the continued healthy growth of the grass, the ongoing materials costs, health and safety risks to users and potential environmental harm from these chemicals – each representing ecosystem disservices – need to be accounted for when assessing the suitability of NbS and in comparing these to maintenance requirements of grey alternatives. In addition, although some tram service level, grass growth performance and maintenance resource requirements data are available relevant to the VSA green track, data gaps make it difficult to perform a full CBA for the green track and compare this to a concrete equivalent. The VSA green track was installed for aesthetic purposes; however, the value of this benefit has not been quantified, nor has the range of other ecosystem services the grass delivers. This will be a vital step in influencing future decisions on the wider implementation of NbS (Blackwood & Renaud, 2022) (Table 5-2: Learning from both cases).

Extra maintenance was identified as the biggest problem encountered by rail industry professionals with experience in NbS implementation (Blackwood et al., 2023); while the VSA grass track requires regular management with associated expenditure and resources, the tram track has not been found to require additional maintenance or repairs compared to standard concrete track [VSA G2P1]. Although green track has been a tried and tested concept for light rail networks (Pfautsch & Howe, 2018), evidence is still required on NbS use on heavy rail infrastructure, and to assess the impact that its presence may have on railway infrastructure (Blackwood & Renaud, 2022). VSA's city centre location provides easy visibility of and access to the green track to monitor and maintain the grass (Table 5-2: VSA - Aid); this may not be the case for rural locations more likely to be encountered for heavy rail infrastructure, which can stretch for thousands of kilometres in remote, hard-to-reach locations. Additionally, the high frequency of tram services combined with the NbS type (grass) means the passing of trams at VSA and on other urban light rail networks will wear down grass growth, helping to prevent operational or safety issues being caused by the vegetation becoming overgrown. Lower frequencies of services in rural settings would prevent such wear, and monitoring would be more difficult in remote locations, therefore, depending on the type of concept applied and its growth rate, this could make NbS an unattractive option, especially if the vegetation needs to be maintained more frequently than the remainder of/surrounding rail infrastructure needs to be examined, thus increasing the number of inspections and associated travel and other resources required. Focus group discussions revealed that there is no specific inspection checklist used in maintaining or monitoring the green track. This has not been deemed necessary for VSA, but research participants agreed that this tool could be useful for other locations, especially if there are new NbS installations introduced, to provide a prompt on what to check for [VSA G2 P1,P2 & P3] (Table 5-2: Learning from both cases).

Table 5-2 Key observations and learning from two case studies into the use of NbS as CCA for rail infrastructure

Research Question/ Objective	Victoria Square Adelaide	Brumber Hill Culvert	Both - Learning acquired from the analysis of both cases
RQ1, RO 1: Challenges and barriers to NbS implementation	• Project delivery in a highly urbanised environment. • Staff training and operational safety procedures are required to enable safe access to the rail corridor for grass maintenance. • Maintenance activities create environmental nuisance to stakeholders. • Technological advancement of grey CCA alternatives.	• (Unconfirmed) Mammals burrowing into the green/grey structure.	• Operational and Maintenance considerations must include: Personnel, equipment and associated access logistics, irrigation and chemicals.
RQ2, RO2: Aids to NbS implementation	• Interface agreement to formalise maintenance roles and responsibilities.	• Key decision maker was an advocate for innovation and sustainable solutions.	• CBA template should be developed to allow identification, measurement and comparison of ecosystem services and disservices, throughout NbS lifecycle.

Research Question/ Objective	Victoria Square Adelaide	Brumber Hill Culvert	Both - Learning acquired from the analysis of both cases
	• Involvement of stakeholders between rail infrastructure life cycle phases. • Urban location aids accessibility for inspection and maintenance.	• Located out with railway owned land. • Design considerations should extend beyond the intervention site and involve stakeholders with whom there will be interactions and interdependencies. • Programme carbon & biodiversity targets drove innovation and sustainable solutions. • Climate models. • Construction plant-free installation.	This should be reviewed, and updates recorded during and between lifecycle stages, and be formally handed over/made available to stakeholders. • Move completion of CCRA to the Planning Phase. • Operational phase feedback should be provided to planning and maintenance, not only design. • Operation & Maintenance stage vegetation management guidance and tools should be retained for handover upon decommissioning to aid the continued upkeep of any remaining NbS. • Use of pre-grown and quick grow solutions provided prompt ecosystem service provision • Recommended tools:

Research Question/ Objective	Victoria Square Adelaide	Brumber Hill Culvert	Both - Learning acquired from the analysis of both cases
			○ NbS selection criteria checklist. ○ NbS inspection & maintenance checklist. ○ Obtain rail industry approval/acceptance of NbS solutions including hybrid options.

5.5 Vegetated culvert headwall at Brumber Hill, Yorkshire, UK

5.5.1 BHC Planning

Due to the scope and location of the repair works required, the replacement of the BHC headwall did not require formal planning consent. Permission for works to the culvert was granted by the owner of the land through which BHC passes [BHC G1P1], and the TRU team undertook liaison with the Internal Drainage Board (IDB) and Environment Agency authorities who were happy with the planned installation (Rail Director, 2022) [BHC I2]. The culvert's location on non-railway land made the decision to use a hybrid NbS option "lower risk" as there was deemed less potential impact to railway assets and operations should the NbS compromise the infrastructure's integrity [BHC G1P1, BHC I2] (Table 5-2: Aid - BHC). The IDB are hopeful that the solution is robust and, if its implementation is effective at this location, would be keen to apply the hybrid solution in their own land drainage management practices, and encourage its use by other landowners whose activities they regulate [BHC I2]. This presents a (potential cross-sector) co-development opportunity for joined up solutions which provide hybrid CCA solutions for rail and adjacent infrastructure and/or landowners. The potential impact of CCA measures on adjacent and/or downstream stakeholders (and vice versa), particularly where changes may affect drainage due to the interconnectivity of drainage networks (Network Rail, 2021a), highlights the need to consider such relationships and interdependencies when designing CCA interventions, including those incorporating NbS. As per the IUCN recommendation, the design of NbS should consider risks beyond the extent of the immediate intervention site (IUCN, 2020). The CCRA process should therefore involve multiple participants and consider the dependencies on and interactions with other stakeholders (Blackwood & Renaud, 2022) (Table 5-2: Aid – BHC). The importance of the Framework's NbS co-development step is confirmed by the successful agreement of a solution with the BHC landowner, which was critical to the success of the rail project delivery. The planning phase regulatory consultation undertaken for BHC also confirms the value in increasing NbS awareness for standard and regulation-setting bodies who can influence planning decisions, e.g., by including specifications for construction methods and materials to comprise NbS.

Works undertaken to BHC were planned in accordance with the TRU sustainability mission statement which commits to building and operating a railway that enhances the environment, and specifically to “preserve and enhance the natural landscape to increase biodiversity and deliver a minimum 10% net gain” (TransPennine Route Upgrade, 2023b) (p. 15). Rail organisational strategy and commitments, typically set during a rail infrastructure project’s planning phase, can therefore help drive the inclusion of innovative and sustainable development, such as the use of NbS for CCA (Table 5-2: Aid – BHC). The business-as-usual approach for culvert headwalls is typically pre-cast concrete sections [BHC G1P1], gabion baskets or a single concrete pour [BHC I2], however interview and focus group participants noted the significant role that a TRU Engineer played in selecting the use of Flex MSE ®, recommending its implementation on sustainability and innovation grounds [BHC I1, BHC G1 P1 & P2] (Table 5-2: Aid – BHC). This highlights the importance of educating rail industry professionals, particularly those in positions to influence decision making, on the availability of NbS as complements and alternatives to grey CCA options, this is bolstered by the TRU delivery contractor expectation that innovative practices are promoted from the top down by the client [BHC G1P1]. For example, the project Sponsor (who provides interface and governance between the rail infrastructure organisation and the project deliverer(s) (Association for Project Managers, 2016)) was recognised as a key stakeholder who can shape such project delivery requirements; a focus group participant suggested that Sponsor requirements could set out a hierarchy which mandates the use of green solutions unless reasonable justification is provided to use an alternative [BHC G1P2]. These observations confirm that the education of relevant rail professionals is a critical Framework activity, particularly for those involved in the rail infrastructure planning stage who influence the selection of, and set the precedence for the management of, a railway asset including its protection from and/or adaptation to the impacts of climate change from its inception; adequate time and resources (training materials and personnel) will be required to provide this [BHC G1P1] (Table 5-2: Learning from both cases).

5.5.2 BHC Design

The TRU programme has used climate models to assess changing weather patterns along the route and identify risks early in the design process, for example the exposure of earthworks to erosion and landslips (TransPennine Route Upgrade, 2023b). Mitigation measures, including NbS, have subsequently been incorporated into the infrastructure upgrade design to provide more resilience to cope with hazardous events and maintain its essential function (IPCC, 2022), with a view to delivering increased rail service reliability and improved customer experience (TransPennine Route Upgrade, 2023b). This confirms that CCRA has been undertaken on TRU, as recommended in the Framework as a key mechanism to integrate NbS into the design of CCA measures (Table 5-2: Aid – BHC), however it was noted that existing CCRA processes do not yet direct practitioners to green options [BHC G1P1 & P2]. For instance, the TRU weather resilience plan triggers the inclusion of added capacity for culverts to “future proof” them to withstand future climates and meet wider sustainability objectives relating to carbon reduction, social value and net gain, however the strategies are “not yet joined up with green infrastructure”, which could simultaneously support multiple organisational sustainability objectives [BHC G1P1] (Blackwood et al., 2022) whilst also delivering CCA benefits. A flow chart with associated guidance to take practitioners through the CCRA process and provide direction on suitable NbS options is suggested as a tool to aid selection of sustainable CCA options [BHC G1P2] (Table 5-2: Learning from both cases). Further, focus group participants believe the development of a comparison tool to evaluate, for example cost and carbon, differences between options would aid the selection of more sustainable options [BHC G1P1 & P2], it is felt that specific TRU carbon reduction targets have driven the consideration of more innovative solutions with the project delivery team receiving more requests to trial new construction materials and methodologies [BHC G1P1].

Flex MSE ® suppliers provide a range of practical considerations to help inform the incorporation of the product into infrastructure design including, for example, the application for which the solution is being used, site drainage, wave action, stream scour depths, exposure to sunlight and wind, and nutrient availability (Flex MSE, n.d.). It is also recommended that long term maintenance and water access be considered when designing the product install which will depend on local climate, plant choice, and the timing of planting (Flex MSE, n.d.). The involvement of geotechnical engineers and vegetation specialists is therefore recommended in the rail infrastructure and NbS design phase, this aligns with the Framework's involvement of multidisciplinary stakeholders during and between rail infrastructure lifecycle stages. Rail infrastructure operators and maintainers should therefore participate in the design process so that they can contribute to the selection of suitable NbS options based on their knowledge of and experience of managing vegetation and of the NbS installation site, as successfully demonstrated in the VSA case (Table 5-2: Learning from both cases). Stakeholders involved in the design of BHC included TRU project team members, the IDB, Environment Agency, the product supplier and landowner (Rail Director, 2022) [BHC I1 & I2, BHC G1P1].

Whilst successful in gaining support for use of the hybrid Flex MSE ® option at BHC, a general reluctance by the rail industry to move away from traditional systems and its tendency to undertake "like for like" replacements were noted as key challenges to the uptake of NbS for CCA [BHC I1, G1, P1&P2] (hybrid grey-green solutions have been recommended as aids to the phasing in of NbS to the rail sector (Blackwood & Renaud, 2022; Blackwood et al., 2022) on this basis). BHC G1P1 spoke of the common misconception that grey concrete options are "heavy by their nature and therefore must provide stronger retention than green solutions". They therefore feel that managing a change in mindset to overcome this mistaken belief, and apprehension to try something new, is particularly difficult in rail. A TRU delivery contractor advised that having NbS use specified by the design team would result in a much higher chance of the product being installed on site [BHC G1P1]. Recognising that designers are generally the "technical experts", it is felt that the onus is on them to specify what is/is not technically feasible and, as mooted for the planning phase, the suggestion was made that a hierarchy approach be applied, with NbS at the top and designers having to justify why they are unable to implement green options, before moving down the hierarchy of hybrid and then grey options [BHC G1 P1&P2]. The use of 'historic' standards which fail to include NbS options, was described as a clear blocker to the roll out of new materials, and it is felt that rail industry innovation moves "at a snail's pace" [BHC G1P1]. The deployment of a novel solution or product on a major project can be seen to "open the floodgates" for its implementation elsewhere [BHC G1P1], however, this aligns with a wider industry optimism that it is becoming easier to get new products approved (Rail Director, 2022). The implementation of vegetated wall systems in rail infrastructure may be aided by Flex MSE ® being confirmed as complying with 'HAPAS' (Highways Authority Product Approval Scheme) requirements, following its independent testing by the British Board of Agrément (British Board of Agrément, 2022; Highways Industry, 2023). Whilst not a railway approved product, as required in Great Britain by Network Rail's Product Acceptance (Network Rail, 2023) process or Australia through the Australian Standard AS 7702 Rail Equipment Type Approval (Rail Industry Safety Standards Board Ltd., 2023), for example, HAPAS certification should help demonstrate that the concept is fit for purpose, having passed rigorous structural and durability assessments. As recommended by the Framework, cross-sector collaboration to support the approval and promotion of innovative solutions, such as Flex MSE ®, may help benefit multiple industries and enable the collective implementation of NbS for CCA, which could help provide greater cumulative benefits at the landscape scale (Table 5-2: Learning from both cases).

5.5.3 BHC Construction

Comprehensive product installation techniques are provided by Flex MSE ® suppliers (British Board of Agrément, 2022; Flex MSE; H. B. B. Geosales) and the quick build time cited (two thirds to half that of conventional walls (Flex MSE, 2023b)) is a clear selling point for the product. The modular wall structure can be vegetated during or after its construction using the following planting methods: hydroseeding (the quickest and most common option, a process of spraying a sticky seed mixture to the exposed surfaces when built [BHC I1]), live punching and planting directly into the bags, or brush layering, where roots of more established plants can be positioned behind/between the Flex MSE ® Bags (Flex MSE, 2023a). The growth time for NbS to fully establish and provide maximal CCA (and other ecosystem services (Millennium Ecosystem Assessment, 2005)), combined with seasonal planting windows (Flex MSE), may be regarded as constraints to their implementation however, especially when compared to grey alternatives which generally provide immediate solutions (Albert et al., 2019; Kumar et al., 2020). Despite this, the benefits of fast, construction plant-free installation of Flex MSE ® will be particularly advantageous to the rail industry where infrastructure works are generally conducted during engineering 'possessions' where the track is closed to normal rail services to enable the safe completion of maintenance and improvement activities (Network Rail, n.d.), as would be required for the installation of CCA measures on operational railways (Table 5-2: Aid – BHC). Short duration possession windows with minimal construction logistics are preferable in order to minimise disruption to train services, and it is felt that these time constraints continue to drive like-for-like replacement, with a TRU delivery contractor stating "too often we are in and out with a business-as-usual approach, resulting in similar replacements and upgrades" (Rail Director, 2022, p.63), and a focus group participant confirming that project delivery program constraints mean that engineers default to what they've used before [BHC G1P1]. Whilst not located directly on railway infrastructure, promoting the quick and easy delivery of the vegetated culvert solution on a rail project at BHC may help with the shift from traditional designs, materials and delivery methods that is deemed necessary to meet both project and government targets relation to carbon and biodiversity net gain (Rail Director, 2022). The extent of this benefit should be quantified in the CBA undertaken during CCA option selection (Table 5-2: Learning from both cases).

Regarding carbon benefits of the hybrid CCA option, the Flex MSE ® polypropylene bag and plates comprise 100% recycled content and the system allows for the reuse of excavated spoil, avoiding the need for carbon-intensive concrete, rebar and/or wire mesh alternatives; meanwhile, the manual installation of the product at BHC averted the need to use fuel-consuming and emissions-generating construction plant required for traditional grey CCA measures [BHC I1] (Flex MSE, 2023a). Use of the product at BHC will therefore have contributed to TRU sustainability targets to reduce the carbon impact of construction by up to 30% (TransPennine Route Upgrade, 2023b), viewed as a selling point for the products use, but, as discussed in the preceding BHC design section, the use of a comparison tool would confirm this [BHC G1P2], and support decision making through the CBA carried out to inform the selection of CCA measures.

5.5.4 BHC Operation

Stakeholders have confirmed the successful growth of vegetation on the BHC structure, and validated the Flex MSE ® system's performance as a culvert headwall [BHC I1 & I2, G1P1] (Monteiro, 2017). A TRU delivery contractor confirmed that the product has got "greener and greener" over two years of growth (see **SI 3**); referring to the headwall as a "living structure", they are hopeful that the supply and installation of the vegetated headwall concept on a rail project will strengthen the evidence for its use elsewhere [BHC G1P1]. Data is not yet available to confirm the effectiveness of the CCA integrated into the culvert, however. Due to the small scale of the installation, biodiversity gains are thought to be negligible however as well as noting the aesthetic value of the vegetated structure ("it looks amazing"), study participants complimented the "softer landscaping" and "connected landscapes" [BHC G1P1, P2]. The attractiveness of the culvert as a wildlife habitat may present an ecosystem disservice, however, with one participant observing a small hole on the structure they believe may have been created by a burrowing mammal [BHC I1]; should this be the case the structural integrity of the culvert and the effectiveness of the CCA measure may be compromised posing a very real barrier to the success of this installation and to the potential uptake of the concept elsewhere, despite the 120-year design life (British Board of Agrément, 2022) and 75-year warranty (Flex MSE, 2023b) for the Flex MSE ® product (Table 5-2: Barrier - BHC). It will be important for NbS performance (e.g., CCA effectiveness, operational impact on rail services, biodiversity contribution), to be formally measured and recorded for reference during the long-term operation of the rail/NbS asset, and to better inform future CBA undertaken when considering the use of NbS elsewhere (Table 5-2: Learning from both cases).

5.5.5 BHC Maintenance

The vegetated headwall has been in place for two years at BHC, the Flex MSE ® structure is maintenance free, with only minor de-vegetation having been required to date [BHC G1P1], this is thought to be largely down to the small scale of the culvert and the seedbank selected. It is recognised that vegetation may be challenging to maintain on larger structures e.g., some railway embankments require abseilers to conduct vegetation management, this ecosystem disservice may present a blocker to NbS use elsewhere [BHC G1P1]. Focus group participants were quick to highlight that should NbS require maintenance practices that are different to or more onerous than usually required, it would be critical to justify the benefits of the new solutions to the asset's maintainers, and that such discussions would have to be held and agreements for long-term management made early to get stakeholders on board [BHC G1 P1 & P2]; the earlier recommendation to include maintainers in NbS planning would enable this (Table 5-2: Learning from both cases).

A formal maintenance/inspection checklist is not thought to be in place for the BHC [BHC G1P1], Flex MSE ® suppliers recommend that regular structural inspection and maintenance regime is undertaken, with inspections being at least annual and after any major seismic or climatic event (Flex MSE, n.d.). Remedial measures to aid vegetation growth on the headwall may include irrigation, application of fertilisers and herbicides (Flex MSE, n.d.), and the re-application of vegetation; these maintenance activities may require extra financial cost to buy in specialist support, or the provision of inhouse resources or training of existing staff, to provide internal capability for this, representing ecosystem disservices as per the maintenance of VSA grass track. Completing routine inspection and maintenance of the NbS will provide the opportunity to formally observe, measure and record NbS performance; this will support the formal quantification of NbS ecosystem services and disservices which will aid future CBA undertaken to select new and/or additional CCA measures, and therefore potentially strengthen the business case for the use of NbS. Consideration of the maintenance regimes required for both the grey and green components of the hybrid CCA solution at BHC cues the potential to merge these into one integrated activity that can be completed by one, rather than multiple parties, providing a more efficient maintenance approach. As above, this would likely require the training of maintenance personnel and the development of procedures and guidance (Table 5-2: Learning from both cases). Treating hybrid CCA solutions, such as BHC, as one asset rather than separate NbS and rail infrastructure components aligns with the recommendation that railway lineside vegetation should be regarded as a rail asset and managed as per other rail infrastructure, such as signalling and track (Rail Safety and Standards Board Ltd., 2018). This approach would formalise the management and condition monitoring of any NbS incorporated into infrastructure, providing data to enable better quantification of the CBA for NbS, additionally, integrating NbS maintenance with business-as-usual activities could help to counter the perceived reluctance to the changing of current rail practices [BHC I1, G1, P1&P2] (Blackwood & Renaud, 2022; Blackwood et al., 2022; Blackwood et al., 2023); this would initially be beneficial for hybrid CCA solutions, but with time may extend to improve and accelerate the acceptance of purely green NbS utilised in the rail environment.

5.6 Rail infrastructure and Nature-based Solution decommissioning phase

As explained in Chapter 5.2, the rail infrastructure/NbS Decommissioning lifecycle stage was not explicitly considered during the focus groups or interviews. The Decommissioning phase could entail the disbanding of either NbS and/or railway infrastructure from a location. For railway infrastructure, this process would generally involve the dismantling and removal of assets, e.g., rail, signals and sleepers (Government of South Australia, 2023b) (which may include NbS that have been integrated with rail assets as part of hybrid CCA measures), or they may be left in situ. If the former, and the land is not redeveloped, this could allow standalone (i.e., non-hybrid) NbS to spread into the footprint of the removed infrastructure, increasing local ecosystem benefits (and potentially also disservices). If the latter were to occur, and infrastructure remains in place without trains operating on it, this too could enable vegetation to thrive, a notable example being the High Line greenway upon what was previously a rail line in downtown New York, United States, where over 500 species of plants and trees now provide an attractive green space (Friends of the High Line, 2024).

Should remaining NbS no be longer maintained post-decommissioning of rail infrastructure, a lack of irrigation, for instance, could cause the vegetation to die off with detrimental impacts to biodiversity, adjacent landowners and the local community. If the rail corridor were to be redeveloped, the impact on the NbS would depend upon the new land use. To maximise the health and longevity of any NbS remaining on the land post-decommissioning, ideally the vegetation management and inspection tools generated during the Operation & Maintenance lifecycle phase should be retained (especially if the land is kept by the rail infrastructure owner, who could potentially continue to maintain the NbS). Should the land be sold or leased, the Operation & Maintenance information could be provided in a handover pack to the new maintainer to aid their continued upkeep of the vegetation.

Whilst rail infrastructure that is removed from one location may be suitable for reuse elsewhere (if not life expired) (Sañudo et al., 2022), the uplift and replanting of vegetation elsewhere may have limited success. The sustainable design of infrastructure assets to enable easy separation on disassembly into materials suitable for reuse and recycling is encouraged (Infrastructure Sustainability Council, 2021a), this concept may also benefit the planning of NbS (both standalone features and hybrid with rail infrastructure) into modular "plug and play" options (e.g., (GreenBlue, 2024), which could provide more portable options that allow the movement of NbS upon decommissioning.

If the decision is made to decommission NbS independently of the rail infrastructure (potentially due to poor vegetation growth and/or CCA performance, high maintenance resource requirements, or operational/safety concerns, for example), the vegetation may be removed or potentially left to die. The rationale for decommissioning the NbS should supported by performance records logged during the Operation & Maintenance phase, and learning gained over its lifecycle should inform the future consideration of NbS implementation. In this scenario, rail infrastructure owners should also seek alternative CCA measures to protect their assets from and/or adapt it to accommodate climate change impacts.

Whilst it may be difficult to forecast decommissioning timescales and/or the actors involved potentially decades in advance, in order to try to futureproof the management arrangements for NbS used on rail infrastructure, the decommissioning stage should be considered from the offset i.e., at all steps in the framework which involve full asset lifecycle considerations.

5.7 Case study outputs

Key observations and inferences from the analysis of the use of NbS as CCA at VSA and BHC, and their alignment with this study's research questions and objectives, are summarised in Table 5-2 These findings have been used to refine the 2022 Framework proposed by Blackwood & Renaud (Blackwood & Renaud, 2022), as described in Table 5-3, to create an enhanced tool intended for use by the rail industry to integrate NbS into their infrastructure, presented in Figure 5-4.

Table 5-3 Observations and learning from case studies applied to initial Framework to incorporate NbS as CCA measures for rail infrastructure

Framework phase/process (as per Figure 5-1)		Case study learning/observation	Update made to framework (as shown on Figure 5-4)
Rail infrastructure risk management		The holistic rail infrastructure risk management approach is confirmed as an essential backdrop to the successful implementation of the framework.	No change made.
Climate change risk assessment		• Whilst already featured as a key framework step, the climate change risk assessment process should be integrated as part of, rather than be a 'bolt on' that is separate to, the rail infrastructure lifecycle. • This process should involve multiple disciplines (including external stakeholders) and consider interactions with, and dependencies on, other sectors and stakeholders.	• Climate Change Risk Assessment has been made a key stage in the linear framework (i.e., it is no longer a separate phase). • The involvement of external stakeholders and the consideration of landscape scale relationships and interdependencies is included in this framework stage.
Promoting rail sustainability benefits	2	Confirmed as a key enabler, this activity should be undertaken throughout the rail infrastructure and NbS lifecycle stages.	This activity is now included as an input to the overall framework, rather than featuring at only certain stages.
Multidiscipline participation	3	Participation at all rail lifecycle stages should involve stakeholders from different disciplines ***and*** other rail lifecycle stages.	This activity is now included as an input to the overall framework, rather than featuring at only certain stages; it has been expanded to include multi-lifecycle stage participants and impacted stakeholders.
Cross-sector and cross-regional collaboration	4	Each approach has been confirmed as being an aid to the successful roll out of NbS for CCA on rail infrastructure. These activities should be undertaken throughout rail infrastructure and NbS lifecycles.	These activities are now included as key inputs to the overall framework, rather than only featuring at certain stages.
Semi-open corridors	5		
Open-air laboratories	6		
Research impact of vegetation	7	Whilst not mentioned in the case studies as a specific activity to support NbS uptake, research into the impact of vegetation	Removed as a specific framework step.

Framework phase/process (as per Figure 5-1)		Case study learning/observation	Update made to framework (as shown on Figure 5-4)
		in the rail environment could be included as part of open-air laboratory trials in the rail environment. Remove as a specific framework step.	
NbS standards and guidance for rail	8	Specific tools have been suggested (and requested by research participants) to aid NbS implementation at different stages of rail infrastructure/NbS management lifecycles.	The framework has been supplemented with the various tools suggested and requested through this research.
Quantify NbS benefits	9	Confirmed as a critical activity; this must include NbS benefits ***and*** disservices. Cost Benefit Analysis should be completed and recorded at all lifecycle stages to allow comparison between planned versus actual performance and enable the sharing of data to inform decision making on NbS implementation elsewhere.	From the Climate Change Adaptation Option Selection stage onwards, the framework requires inclusion of benefits and disservices, and the recording and sharing of outputs at each stage, to inform future Cost Benefit Analysis and subsequent decision making on NbS selection and management.
Rail infrastructure lifecycle stage: Planning	Planning	Additional aid identified: • NbS selection criteria and guidance	This tool has been added to both the Planning and Design phases, with each of these stages now extending to encompass the NbS lifecycle (they previously only covered rail).
Rail infrastructure lifecycle stage: Design	Design	Key activities identified for inclusion: • Confirm vegetation source and growth time • Incorporate operation and maintenance features • Refine Planning phase Cost Benefit Analysis	The activities have been added to the Design phase which has now been extended to encompass the NbS lifecycle (previously only covered rail).
Rail infrastructure lifecycle stage: Construction	Construction	Key activities and tools identified: • NbS installation guidance • Retain NbS installation records • NbS handover pack containing operation and maintenance requirements • Refine Design Phase Cost Benefit Analysis	The activities and tools have been added to the rail infrastructure Construction/NbS installation phase (the latter has been differentiated from rail infrastructure 'Construction' with a more appropriate descriptor).

Framework phase/process (as per Figure 5-1)		Case study learning/observation	Update made to framework (as shown on Figure 5-4)
Rail infrastructure lifecycle stage: Operation	Operation	Key activities and tools identified: • Interface agreement to confirm roles and responsibilities • Vegetation management guidance and training • Inspection and maintenance schedule and checklist • Records of operational performance • Record planned versus actual operational and maintenance requirements • Refine Cost Benefit Analyses from earlier lifecycle stages	The activities and tools have been added to the Operation & Maintenance phase.
		NbS performance (including benefits and disservices) should be recorded and made available to share at all lifecycle stages - not only during Operations – to support future Cost Benefit Analysis to aid decision making in the implementation of NbS at other locations.	As above, the framework now requires inclusion of benefits and disservices, and the recording and sharing of outputs at each stage from the Climate Change Adaptation Option Selection stage onwards, to inform future Cost Benefit Analysis and subsequent decision making on NbS selection and management.
Rail infrastructure lifecycle stage: Decommissioning	Decommissioning	Key activity identified: • Retain Operations & Maintenance phase guidance and tools to provide a handover pack to aid the continued upkeep of any remaining NbS.	This activity has been added to the Operation & Maintenance phase and referenced in the Decommissioning stage.
Validation of NbS options for rail	Co-Development	Co-development is included as a step in the Validation of NbS options for rail process, this should be extended to apply to the wider development of climate change adaptation options.	This activity is now included as a key input to the overall framework rather than featuring only at certain stages.
Incorporation of NbS as CCA options for rail	9	Cost Benefit Analysis should be undertaken to inform the selection of climate change adaptation options, to include NbS services and disservices across the full asset lifecycle.	The previous activity to ‘Quantify NbS benefits’ has been expanded to also consider ecosystem disservices, and across the full lifecycle rather than only featuring at certain stages.

Framework phase/process (as per Figure 5-1)		**Case study learning/observation**	**Update made to framework (as shown on Figure 5-4)**
Aids to NbS implementation	❶ to ❾	Additional aids to NbS implementation were identified as: • Pro-NbS Planning Policy and legislation • Education and awareness on NbS for rail industry, regulators and standard setting bodies • Sharing of demonstration projects across rail industry and of NbS practices between railway and climate analogues • Rail organisational sustainability policy, objectives and targets • Benchmark schemes and incentives for use.	The additional aids have been added as framework inputs.

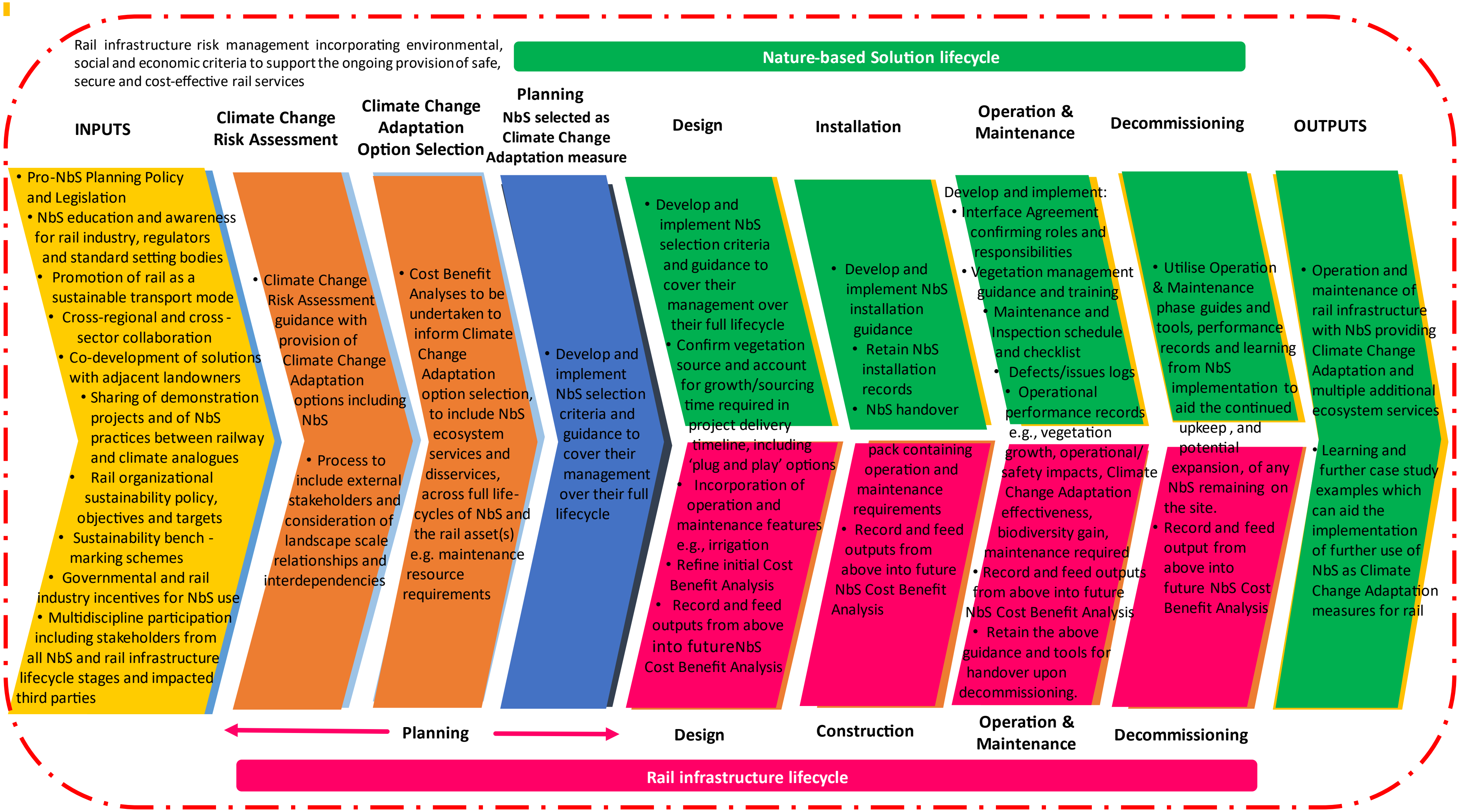

Figure 5-4 Revised framework to incorporate Nature-based Solutions as Climate Change Adaptation measures for rail infrastructure

5.8 Conclusion

With rail industry professionals citing a lack of awareness on NbS as the most significant barrier to their uptake as CCA measures by the sector, the promotion of NbS concepts is crucial to their dissemination. This research showcases two examples of NbS being applied in live rail environments, providing CCA functions amongst other valuable ecosystem services. The case study outputs provide tools to both educate on, and increase visibility of, the successful implementation of NbS on rail infrastructure. Further, by collating and evaluating key observations from the cases, including valuable feedback from stakeholders involved in each, an enhanced framework has been developed to provide a practical approach to embed and upscale the application of NbS for the CCA of rail infrastructure, thereby supporting the ongoing provision of safe and sustainable rail services.

Testing the framework on locations with different contexts, climates, and stakeholders helps validate its suitability, however, its application on more live rail scenarios will enable further refinement. In the meantime, outputs obtained through use of the framework will build more evidence on the success of NbS as a CCA measure for railways, supporting the continued integration of the concept into the industry.

Chapter 6 Conclusion

6.1 Summary of findings and implications

This research has assessed the potential to implement NbS as CCA measures for rail. It documents the development of a framework intended for use by the rail industry to support the operationalisation of NbS as a means of protecting its infrastructure from, and adjusting it to accommodate, currently faced extreme weather events and the conditions predicted under future climate conditions (Figure 3-4), and describes its evolution to a second, refined version (Figure 5-4) which has been enhanced through rail industry engagement and learnings from the examination of two case studies. Both figures are inserted below for ease of reference.

Phase	Process	Source
	Rail infrastructure risk management	Author
	Rail infrastructure lifecycle stage	California High-Speed Rail Authority (2021) Government of South Australia (2020) Network Rail (2017) Wordsworth (2019)
	Climate change risk assessment	Standards Australia (2013) The British Standards Institution (2019) Queensland Government, (2020) Transport for New South Wales (2016) Network Rail (2021)
	Validation of NbS options for rail	Kumar et al. (2020)
	Incorporation of NbS as CCA options for rail	Author
	Implementation of NbS in rail infrastructure	Author
1 to 9	Approach/action reference number	Figure 3-3 and Table 3-1

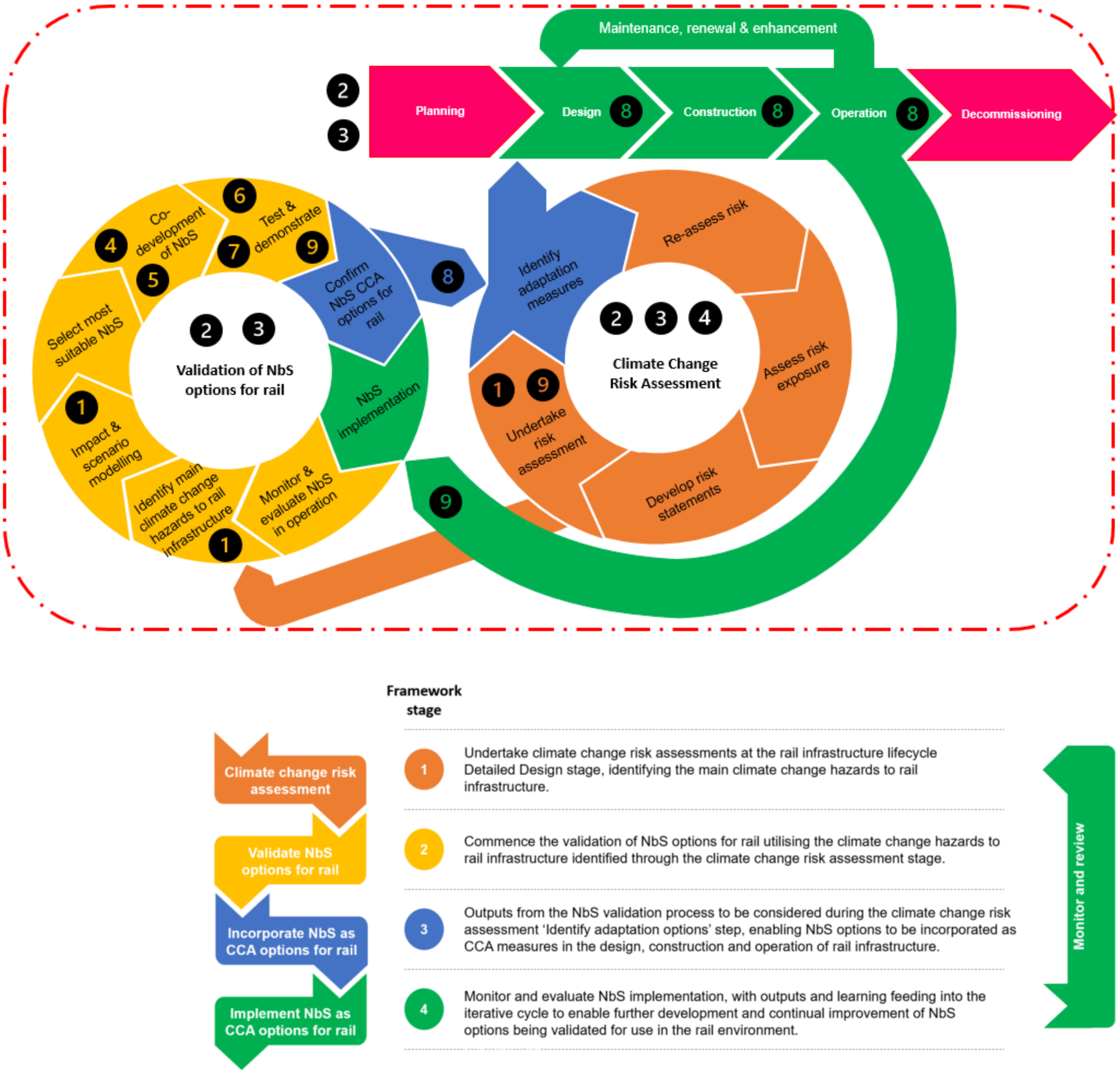

Figure 3-4 Framework to incorporate Nature-based Solutions as climate change adaptation measures for rail infrastructure

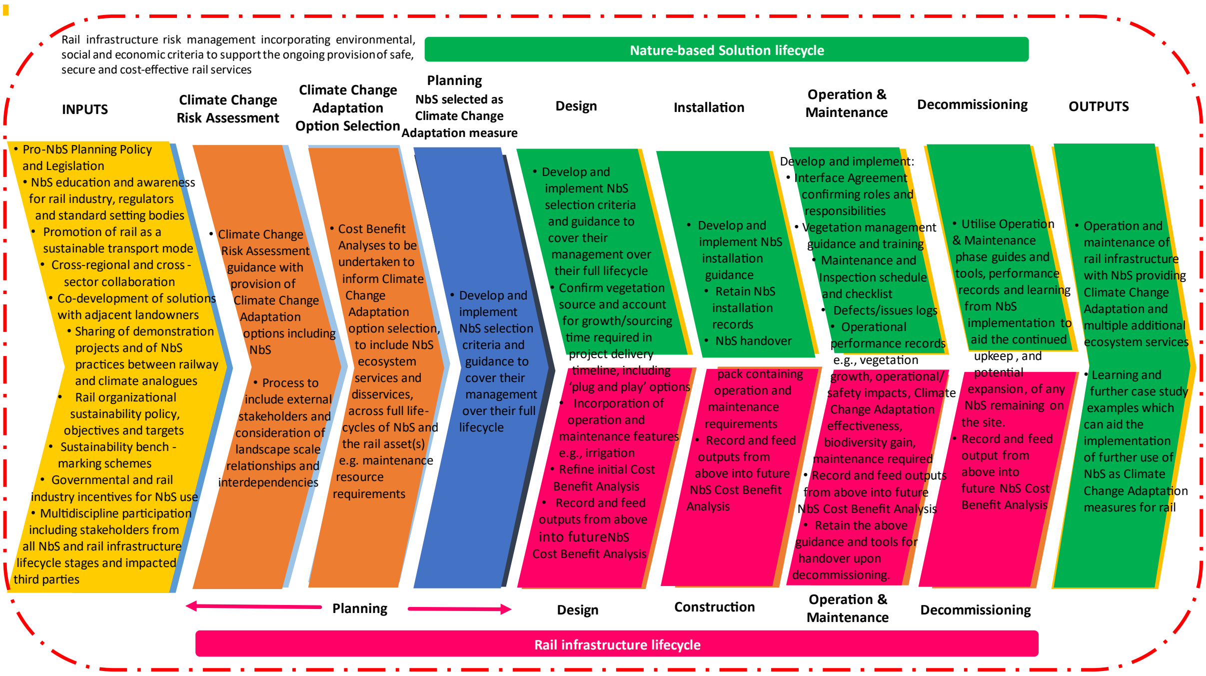

Figure 5-4 Revised framework to incorporate Nature-based Solutions as Climate Change Adaptation measures for rail infrastructure

The research involved the alignment of two, previously separate, bodies of research on CCA for rail and the operationalisation of NbS. Mixed method approaches were applied to address a set of four research questions initially presented in Chapter 1. Examples of NbS in use for CCA in rail are identified, along with NbS concepts used out with the industry which may be transferable to the rail sector. The study then examined potential barriers and aids to the implementation of NbS in the rail context, and used these to develop a rail-specific framework to operationalise NbS for CCA; the barriers and aids were then confirmed, and the framework enhanced through testing and engagement with rail industry professionals in the UK and Australia.

The research outputs are presented in the previous four chapters (Chapter 2 to Chapter 5) which contain the content of four papers published in peer reviewed academic journals. Each chapter builds upon the outputs of the previous research, rather than addressing each research question in chronological order. Table 6-1 provides an overview of how each chapter addresses the relevant research question(s), and summarises the contribution to knowledge made by each paper.

Table 6-1 Summary of research outputs

Research Question (RQ)	**Chapter 2: Nature-based solutions as climate change adaptation measures for rail infrastructure**	**Chapter 3: Barriers and tools for implementing Nature-based solutions for rail climate change adaptation**	**Chapter 4: Rail industry knowledge, experience and perceptions on the use of nature-based solutions as climate change adaptation measures in Australia and the United Kingdom**	**Chapter 5: A framework for the successful application of nature-based solutions for climate change adaptation on rail infrastructure developed through the examination of two case studies**
RQ 1: What is the evidence base on the use of NbS being implemented as CCA measures in the railway context?	The extremely limited evidence base on the use of NbS as CCA for rail in literature is established.			
RQ 2: Are there NbS being used as CCA measures in rail which are not included in the literature?			Through an online questionnaire, rail industry professionals confirm multiple examples of NbS, predominantly in the UK and Australia, that are being used in rail which are not included in the literature.	Research, analysis and dissemination of two rail case study examples, in the UK and Australia, making a direct contribution to literature on the topic.
RQ3: What are the challenges and barriers to the operationalisation of		Derivation of rail industry-specific barriers to NbS implementation from the literature, categorising these into seven key themes:	International rail industry professionals provide their perceptions and observations on barriers to the implementation of NbS for	Identification of the barriers to the implementation of NbS on two live rail locations, including those gathered through interviews

Research Question (RQ)	**Chapter 2: Nature-based solutions as climate change adaptation measures for rail infrastructure**	**Chapter 3: Barriers and tools for implementing Nature-based solutions for rail climate change adaptation**	**Chapter 4: Rail industry knowledge, experience and perceptions on the use of nature-based solutions as climate change adaptation measures in Australia and the United Kingdom**	**Chapter 5: A framework for the successful application of nature-based solutions for climate change adaptation on rail infrastructure developed through the examination of two case studies**
NbS as CCA measures for the rail industry?		Safety concerns, lack of evidence, time constraints, limited cost benefit analysis, land use constraints, climate change uncertainties, and stakeholder dependencies.	CCA through an online questionnaire.	and focus groups with rail stakeholders directly involved in each case.
RQ 4: What could aid the operationalisation of NbS as CCA measures for the rail industry?	The knowledge gap on the use of NbS for CCA in rail is confirmed and recommendations are made for further research into barriers to NbS implementation with a view to aiding uptake by the sector.	Potential tools and approaches to aid NbS implementation are recommended and are used to develop a framework to support the uptake of NbS for CCA by the rail industry.	Rail industry professionals confirm recommended aids to NbS operationalisation based on their perceptions of the concept, and observations and lessons learned from live rail examples of NbS being used for CCA.	Aids to the implementation of NbS on two live rail locations are identified, with sources including interviews and focus groups with rail stakeholders directly involved in each case. The initial (Chapter 3) framework for NbS operationalisation is tested and refined, using feedback from rail industry professionals and learning from two live rail case studies.

Research Question (RQ)	**Chapter 2: Nature-based solutions as climate change adaptation measures for rail infrastructure**	**Chapter 3: Barriers and tools for implementing Nature-based solutions for rail climate change adaptation**	**Chapter 4: Rail industry knowledge, experience and perceptions on the use of nature-based solutions as climate change adaptation measures in Australia and the United Kingdom**	**Chapter 5: A framework for the successful application of nature-based solutions for climate change adaptation on rail infrastructure developed through the examination of two case studies**
Original contributions to knowledge:	NbS are presented as potential CCA candidates for use on rail infrastructure. Potential NbS concepts suitable for application on rail infrastructure are proposed. Examples of NbS being used in non-rail contexts that may be transferable to rail infrastructure are provided. A tool that aligns potential NbS application with rail infrastructure type and the HMH(s) faced is provided.	Rail industry-specific barriers to the uptake of NbS are identified. Potential aids to the uptake of NbS for CCA by the rail industry are recommended. An initial framework for use by the rail industry to support the operationalisation of NbS for CCA is provided.	Chapter 3 literature review conclusions are validated. Rail industry perception and observations on the implementation of NbS as CCA on rail infrastructure are confirmed. Identification of barriers and aids to NbS operationalisation in rail additional to those included in the literature. New primary data and information which may inform and promote practical CCA options for the global rail industry is created and disseminated.	Chapter 3 literature review conclusions are validated. Rail industry perception and observations on the implementation of NbS as CCA on rail infrastructure are confirmed. Additional barriers and aids to NbS operationalisation in rail to those included in the literature, and those stated by rail industry professional through the engagement conducted in Chapter 3 are identified. Research, analysis and dissemination of new primary data and information which may inform and promote

Research Question (RQ)	**Chapter 2: Nature-based solutions as climate change adaptation measures for rail infrastructure**	**Chapter 3: Barriers and tools for implementing Nature-based solutions for rail climate change adaptation**	**Chapter 4: Rail industry knowledge, experience and perceptions on the use of nature-based solutions as climate change adaptation measures in Australia and the United Kingdom**	**Chapter 5: A framework for the successful application of nature-based solutions for climate change adaptation on rail infrastructure developed through the examination of two case studies**
				practical CCA options for the global rail industry.

As well as connecting two research streams and contributing to scientific knowledge on a previously under-investigated topic, this work socialises the concept of NbS for CCA with a rail industry audience, and vice versa, it shares with the academic community the urgent need, and vast opportunities that exist, for further scientific research on this subject. In addition to the above outputs, and to supplement Chapter 5, a third rail-specific case study has been prepared in a format targeted to rail industry stakeholders, to communicate the final version of the framework to incorporate NbS as CCA measures for rail infrastructure (Appendix F).

Table 5-3 provides narrative on the evolution of the Figure 3-4 framework to the revised version shown in Figure 5-4 and as included in the Appendix F case study. The former figure clearly shows the three individual concepts upon which the framework is established (rail infrastructure lifecycle management, CCRA and the validation of NbS for rail), and illustrates the interaction and feedback loops between these processes. Figure 3-4 may therefore be of greater interest to those concerned with the framework's theoretical foundations and their procedural relationships. The Figure 5-4 version of the framework is akin to linear rail infrastructure lifecycle management practices which generally apply a "product, rather than process, driven" stage-gate methodology (Wordsworth, 2019). The format of the latter framework integrates both the CCRA and NbS validation processes into a combined rail infrastructure and NbS lifecycle process flowchart, and includes staged, checklist style input, output and activity criteria (as recommended by Buttrick (2022)) that will enable feedback to and from other rail lifecycle stages and rail infrastructure projects. Figure 5.4 is therefore likely to be more user friendly for the rail audience at which the outputs of this research are directed.

As well as contributing to academic literature, it is hoped that this study's four research papers (Chapter 2 to Chapter 5) and three rail-specific case study publications (Appendices D, E and F) are well received by the rail industry, and that these documents and tools encourage the consideration, and potentially the adoption, of NbS concepts for application as CCA in the sector. Evidence of industry uptake of this research to date is visible (although not fully referenced) in Transport for Wales's 'Climate adaptation and resilience plan' (2023, p. 75). In the same document, Transport for Wales also replicate, but again do not cite, the chart presented in Figure 2-1 which displays the relationships between HMHs and their impact on rail infrastructure (2023, p. 49). This demonstrates early acknowledgment and application of the outputs of this study by the transportation sector.

The recommendation to use case studies as vehicles to promote and share information on NbS concepts, including best practices and lessons learned from implementation, is echoed in all four research papers contained in this thesis. In writing up the case studies contained in Chapter 5, the author has sought to address the shortcomings that the European Commission identify in pilot cases, as discussed in Chapter 2. For example, the case studies avoid the use of overly scientific language, consider the full infrastructure lifecycle, and provide full transparency of all of the pros and cons to NbS implementation disclosed through the research, in order to provide better certainty on NbS performance outcomes (cf. European Commission (2018)).

This study also addresses several of the research gaps identified regarding general CCA planning for the rail industry that are introduced in Chapter 2. For instance, in response to the concern raised by Armstrong et al. (2017), by connecting HMH, rail infrastructure categories and potentially suitable nature-based CCA options, the study outputs confirm the need for adaptation (by rail infrastructure type) with details of potentially suitable CCA interventions (Figure 1-4). Meanwhile, Chapter 3 specifically addresses factors that could restrict or promote the implementation of (nature-based) CCA measures in the rail sector, an issue that is flagged by Wang et al. (2020c) as being a gap in CCA planning for the overall transport industry.

The following sections discuss the limitations of this study, and the implications of this research to the rail sector and the wider research community, including recommendations for future work.

6.2 Limitations of the research

This study's initial research outputs provide recommendations on NbS concepts suitable for use as CCA measures for rail (Chapter 2), and identified barriers and aids to their deployment on rail infrastructure (Chapter 3), obtained through literature review. This means that the recommended NbS have not yet been tested on rail infrastructure and therefore cannot yet be endorsed as suitable CCA measures for immediate application by rail. Also, as confirmed in Chapter 2, the systematic literature review outputs are limited to material sourced through searches using only English language, meaning that some relevant data sources may inadvertently have been left out. This will limit the representation of any non-English research conducted on this topic. This is compounded by the examples of the application of NbS in live rail environments identified in Chapter 2 being located in Australia and the UK, where – coincidentally - the majority of research questionnaire participants reside (Chapter 4), and where the two case studies are situated (Chapter 5). An opportunity for a gatekeeper at the UIC to circulate a link to the Chapter 4 online questionnaire with their 206 member organisations, which would have significantly increased the global reach of the survey, was unfortunately missed due to delays in the University of Glasgow's Ethics approval process. Whilst purposive sampling was conducted to target research participants and identify suitable cases, it was not intentional to concentrate survey participation and/or the case study research on these same, and only two, countries. Additionally, previous research by Pauleit et al. (2021) found examples of the green infrastructure NbS concept to be concentrated in Australia and the UK, which draws a parallel with this study's findings.

The majority of this research has therefore focussed on 'WEIRD' (Western, educated, industrialised, rich and democratic) societies (Henrich et al., 2010), neglecting the global South and the diversity of NbS examples and rail industry responses that may have been obtainable from global South regions. The lack of global South data gained through this study's literature reviews may however reflect a genuine scarcity of NbS and/or general rail CCA occurring in the global South, meaning there are limited examples that could be identified either through literature searches or the subsequent research questionnaire. This finding is consistent with previous research on CCA options for the transport sector which has found literature to focus on the global North (Koetse & Rietveld, 2012), and in the mapping of evidence of NbS usage to address climate change impacts, where only 15% of examples were located in the global South (Chausson et al., 2020). The limited global South representation in this research could also be due to or be exacerbated by the limited presence of, and/or the author's lack of opportunity to engage with, rail professionals in the global South who are involved in this very niche topic. The IPCC confirm that locations and communities in Africa, Asia, Central and Southern America (i.e., global South regions) have high vulnerability to climatic hazards, and that adverse climate change impacts on infrastructure, including transportation, are concentrated amongst residents in economically and socially challenged urban environments (IPCC, 2023). Such environments are most likely to be encountered in regions in the global South, which highlights the importance of developing CCA options for urban rail systems in these regions. Encouragingly, by 2020 64% of the least developed countries (‘LDC’, which generally comprise the global South regions) who made adaptation commitments under the Paris Agreement (United Nations Framework Convention on Climate Change, 2015) have addressed CCA at the national level through legislation, policy or strategy (United Nations Environment Programme, 2021a). Furthermore, over 90% of LDC included NbS concepts in the adaptation elements of their Nationally Determined Contributions (NDC) (*ibid*). The disproportionate inclusion of NbS in CCA plans by lower income nations is influenced by the traditional practices of working with nature observed in these countries (Seddon et al. 2020a), combined with a higher dependency of using ecosystems to provide essential services, and limited finances to invest in technology and infrastructure solutions (Woroniecki et al., 2023). Unfortunately, the NDC include only high-level goals rather than specific deployment approaches (United Nations Environment Programme, 2021a), but all the same, these countries’ appetite towards utilising NbS for CCA present LDC as good candidates to explore the application of this concept on rail infrastructure. Moreover, as discussed in Chapter 2, NbS could present a particularly attractive, cost effective CCA option for the expansion of transportation infrastructure in regions located in the global South (Koetse & Rietveld, 2012). The scope of further research on CCA for rail infrastructure, including the use of NbS, should therefore be extended to incorporate a wider geography and input from a more diverse range of stakeholders, including those located in regions in the global South as a priority (also refer Chapter 6.4).

A further limitation applied to the Chapter 2 literature review was the exclusion of station buildings and light rail systems from the research scope. The heavy rail infrastructure discipline was intentionally chosen as the focus for this study, predominantly as there has already been a large amount of research on CCA and NbS (including nature-based CCA) options for buildings and (non-rail) urban infrastructure similar to station precinct environments, e.g., Faivre et al. (2017), Frantzeskaki et al. (2019), and Stagrum et al. (2020). Meanwhile, a body of research also exists on the use of green track on light rail networks (see e.g., Pfautsch and Howe (2018)). It was therefore deemed that applying the scope of this research to lesser-addressed heavy rail infrastructure would add greater value and make a more significant contribution to knowledge, especially given the relative global length of heavy rail (801,357 million km (International Union of Railways, 2022)) relative to light rail (15,824 km (UITP, 2023)), enabling a greater potential research reach and impact.

In Chapter 2 it is stated that learning from the application of NbS as green track on light rail would be considered when investigating the use of NbS on heavy rail infrastructure. At that early stage of this study, the inclusion of a light rail case study in later research was not envisaged (Chapter 5). The selection of the VSA case was not intentional and throughout the initial case study planning it was hoped to include (at least) two heavy rail cases. It was only through the limited availability of, and accessibility to, appropriate heavy rail examples that the VSA light rail case was selected. Similarly, the BHC case is not situated directly on railway land however it was, again, one of few suitable examples to investigate. The limited number of examples on which to perform case study investigation, combined with the practical and logistical challenges of undertaking international case studies, and the need of the author, as a rail industry professional to avoid personal conflict of interest, have influenced the cases that were possible to examine. Utilising readily accessible cases may therefore be viewed as availability bias (Centre for Evidence-Based Medicine, 2023). Significant learning has been gained through the detailed examination of the BHC and VSA cases, however, and both involved engagement with experienced industry professionals (the BHC case involving stakeholders from the heavy rail discipline, delivering the BHC works as part of a wider heavy rail infrastructure project (Transpennine Route Upgrade, 2023a)). This helps to validate the representativeness of the cases and subsequent research outputs, and mitigate perceived availability bias.

Recognising that the data sources in Chapter 2 and Chapter 3 were limited to literature, the study's later mixed methods research approaches extended to involve engagement with rail industry stakeholders through an online questionnaire (Chapter 4), and via focus groups and interviews as part of the BHC and VSA case study investigations (Chapter 5). Justification for the relatively small number of participants that took part in the online survey is confirmed in Chapter 4, the predominant cause being the purposive sampling technique employed on a very niche subject meaning there is a relatively small population from which to sample. Further engagement on the topic with rail professionals from a wider geography, to reflect a more diverse range of experience, attitudes and perceptions on using NbS is therefore recommended. As discussed above, this should include rail stakeholders in the global South. These interactions will not only help to confirm any common obstacles to NbS uptake as CCA for rail, but also identify additional and/or differing challenges, e.g., political and societal barriers, that may exist beyond those identified through the literature reviews, questionnaire and case study investigations. This wider engagement may also identify more, and different, examples of NbS concepts being applied for CCA in the rail environment. For example, whilst Chapter 4 reveals that 70% of survey participants (and 95% of Australian participants) were familiar with the reefs/mangroves NbS concept, there was limited awareness on reefs or mangroves being used for rail CCA (zero examples provided), and only one example of its use on rail for this purpose was cited, in Brisbane, Australia. Participants based in tropical and subtropical latitudes (which generally align with global South regions) would be more likely to have a higher level of awareness of the mangroves NbS concept, including its application for CCA. This may be, for example, through their knowledge of and/or involvement in coastal afforestation schemes such as those discussed by Rahman et al. (2019). The Australian continent includes tropical and sub-tropical climate zones, which may explain the high levels of survey participant awareness of the reef and mangrove NbS concepts, however over half of the country's rail network that is situated in tropical latitudes (12% of the national total (Australian Government, 2023)) is privately owned and operated by mining companies, and it is generally in extremely remote, inland areas where the use of reefs and mangroves would not be applicable. This means that, even if reefs and mangroves (and/or other NbS concepts) are being used for CCA on railways in tropical Australia, the survey respondents may not be aware of this. Extending the research questionnaire distribution to rail professionals based in a wider range of tropical and subtropical latitudes (additional to those in Australia who participated in the survey) may therefore potentially have revealed more knowledge on or experience with the application of mangroves for CCA on rail. Any such learning gained through consultation with rail stakeholders in the global South could be shared with railway climate analogues, i.e., those suffering (or, more proactively, who will suffer) similar climate change impacts on their railway infrastructure to those experienced in other countries facing the same HMH (Sanderson et al., 2016).

Chapter 5 research is limited in its scope as a collective case study with there being only two cases examined. This limited number of cases could be subject to a common criticism of the case study approach regarding the extent to which a small number of cases can be deemed sufficiently representative for findings to be generalised (Gomm et al., 2009). Using two cases, rather than one singular, and acquiring rich information for each has supported the triangulation of findings to enable the wider generalisation of outputs and recommendations (Yin, 2018), however further research is clearly required to strengthen and confirm these (or otherwise). There is also a possibility that data saturation (Morse, 1995) was not achieved due to the number of participants interviewed being too small to gather all of the required information, meaning that their responses do not represent the views of the majority of the population. To help counter the low number of participants, a high quality of data was sourced by purposively sampling interviewees as recommended in the literature, e.g., Infrastructure Sustainability Council (2021a), Transport for New South Wales (2016), and by substantiating their input using multiple data sources to corroborate evidence. As a result of the detailed responses provided during the interviews and focus groups, it was possible to follow up on a number of leads e.g., Marchant et al. (2020) and Government of South Australia (2017a), which strengthened, and enabled the elaboration on, the direct answers provided during the interview and focus group sessions. Additional limitations of focus groups and interviews are the potential to misinterpret communications which can lead to information being missed and/or incorrectly understood when creating generalizations from data, or for confirmation bias, where the author may have used ambiguous responses to confirm their own viewpoints (Rabin & Schrag, 1999). A rigorous case study protocol was used to both request and record all evidence, an approach as recommended by the Centre for Evidence-Based Medicine (2023) and Yin (2018) e.g., incorporating all positive and negative feedback on NbS implementation for every research question. This bias was further mitigated by sharing interview outputs with the participants for their review post-interview, prior to publication of the data and, as an additional measure to remove further personal biases, the author positioned themself as an outsider to the cases.

The framework to operationalise NbS for rail CCA has been developed through literature reviews and the analysis of empirical evidence from the questionnaire and collective case study. Temporal constraints apply to the survey responses received 10-31 May 2022, and the semi-structured interviews and focus groups conducted between May and July 2023; findings are therefore specific to these periods. The testing of the framework in Chapter 5 was completed retrospectively on rail infrastructure that had already been through the asset lifecycle stages of planning, design, and construction. This means that the framework has not been actively applied at a point when it may influence real time decision making in the management of the infrastructure so as consider the introduction of NbS to the planning, design and/or construction of a live rail infrastructure project, to test the framework in situ. Doing so would help to validate industry reception to the tool (i.e., is the framework followed? Is and/or to what extent is the full process adhered to? Are all involved stakeholders engaged and supportive of using the framework?). In situ testing would also enable the evaluation of the tool's effectiveness, including any amendments required to enhance the framework. One advantage of conducting retrospective testing is that it has enabled the framework to be assessed across multiple stages of the infrastructure lifecycle of both rail cases. The duration of each lifecycle stage, which can span several years for each of the planning, design and construction phases, combined with operational windows lasting over 50 years, would make it very lengthy and logistically complex to trial the framework over the full lifecycle of a rail infrastructure asset; this constraint would have to be considered when planning any future research. The lack of data in the literature and the absence of quantitative NbS performance measurement having been undertaken by stakeholders involved in the VSA and BHC cases, along with practical (time, resource and accessibility) restrictions preventing the author's access to either case study location to personally conduct NbS performance monitoring and evaluation, means that this research does not include data on the performance of NbS nor its effectiveness in providing CCA and/or additional ecosystem benefits and disservices. NbS effectiveness is defined as "the degree to which objectives are achieved and the extent to which targeted problems are solved. In contrast to efficiency, effectiveness is determined without reference to costs" (Raymond et al., 2017, p. iv). As a further knowledge gap, understanding which NbS interventions are effective, and at what cost, is essential to inform decisions on whether NbS interventions can be scaled up and replicated (Dumitru & Wendling, 2021).

Beyond the context of NbS application for CCA in the rail industry, the lack of sufficient quantitative data to evaluate DRR and CCA responses has been cited as a challenge in evaluating options and actions to mitigate the impacts of natural hazards (Dumitru & Wendling, 2021). This problem has been flagged as a particular issue in demonstrating DRR and CCA progress against the Hyogo Framework for Action (HFA) 2005–2015 ('Building the Resilience of Nations and Communities to Disasters') which was aimed at reducing the social and economic impacts of natural hazards (UNISDR, 2005). Subsequent DRR and CCA policy agendas based around the Sendai Framework for DRR (United Nations Office for Disaster Risk Reduction, 2015) and the Paris Agreement (United Nations Framework Convention on Climate Change, 2015) have included the effective measuring of DRR and CCA progress (Dumitru & Wendling, 2021), for example through utilisation of the UN SDG objectives, targets and indicators to improve, monitor and evaluate progress on social and environmental conditions (United Nations, 2023a). Recognising the importance of obtaining data to prove NbS as effective CCA measures that can be successfully applied in the rail environment, this research emphasises the need for robust evidence on NbS performance in the rail environment, and potential metrics that could be applied in this regard are proposed in Chapter 6.3.

To summarise in response to the research limitations discussed above, although the final framework product presented in Figure 5-4 and Appendix F represents the output of a single study which has been restricted by a number of constraints, the framework provides a significant stepping stone for further work that can be built upon and improved through ongoing practical application.

Finally, the promotion of NbS and recommendations aimed at increasing the uptake of the concept in this thesis should not be viewed as seeking to inappropriately influence or coerce its application. Throughout this research all positives and negatives have been disclosed, including the benefits and ecosystem disservices that have been identified regarding the potential implementation of

NbS in the rail environment. This unbiased stance has been aided by the application of mixed research methods. For example, whilst this study's literature reviews have been valuable in gaining a qualitative understanding of the barriers to NbS deployment for CCA in rail (Chapter 3), the outputs may have been deficient due to the author's personal interpretation of the data (Creswell & Plano Clark, 2018). The literature review findings have subsequently been backed up by quantifying the responses from rail industry professionals on this topic via an online questionnaire, however (Chapter 4), and also by reconfirming and bolstering these opinions via focus groups and interviews with rail subject matter experts (Chapter 5). Furthermore, the author's pragmatist epistemological stance sees the consideration of the potential real-world implications of this research's outputs. Throughout this study the need for robust evidence to be acquired to fully validate the use of NbS in the rail environment is reiterated, acknowledging that this is especially important in the safety critical rail industry where the failure of infrastructure could ultimately lead to multiple fatalities. Similarly, it is recognised that the portrayal of the benefits from NbS implementation could potentially be perceived as greenwashing, by misleading readers over the environmental credentials of the concept (United Nations, 2023e). To mitigate against this, emphasis has been placed on the need to undertake comprehensive multi-criteria analyses to collate and quantify all costs, benefits, advantages and disadvantages of proposed CCA measures, involving stakeholders from multiple disciplines, to enable a balanced and informed comparison of options.

6.3 Outlook and way forward – rail

This research has assessed the potential to implement NbS as CCA measures for rail, and has delivered a framework for use by the industry to apply this approach on rail infrastructure (Figure 5-4 and Appendix F). The framework offers a tool for immediate implementation by the rail sector. Obvious next steps from this study would therefore be to use and further test, and where applicable, adapt the framework, preferably in-situ on multiple live rail infrastructure projects in different regions, utilising a range of different NbS concepts in response to the different HMH faced.

However, any subsequent use and/or testing of the framework will be dependent upon the rail industry being aware of NbS, and of the existence of this research and framework. It is hoped that the journal publications of this research, and in particular the case studies demonstrating NbS being applied in practice in the rail context, which are intended for distribution in the rail industry, will therefore be helpful in this regard. As confirmed in the literature review presented in Chapter 2, whilst very few studies have previously been conducted on NbS as CCA measures for rail, there are fundamental knowledge gaps on more general CCA in the rail context that urgently need to be addressed (Armstrong et al., 2017; Wang et al., 2020a). It is therefore recommended that, as a priority, wider industry awareness on the potential impacts of climate change to rail infrastructure is increased, and that the potential of NbS as a CCA candidate is shared as part of this upskilling. The education, training and awareness materials required by the rail sector could be bought in via specialist consultants (including academics) and/or inhouse capability could be enhanced through the training of rail employees. Accessibility to rail-relevant information in user friendly language will be key to this upskilling (Rail Safety and Standards Board Limited, 2016). To support this learning, and in response to the fourth research objective, specific outputs from this research intended – and recommended - for use by the rail sector in CCA planning and the selection of CCA options include:

- A collation of the impacts to rail infrastructure caused by a range of HMH, and the CCA measures that are currently applied in response to these impacts (Table 2-1).
- Diagrammatic tools that align:
  - Rail infrastructure types and the HMH they are impacted by (Figure 2-1), and
  - Potential NbS that may be applied to rail infrastructure in response to HMH exposure (Figure 2-4).
- Three case-study publications (Appendices D, E and F).

Rail industry learning opportunities on NbS could be provided through the development of and access to pilot sites on rail infrastructure, allowing firsthand visibility of live rail examples. Testing the framework on rail infrastructure in the global South would enable the tool to be finessed so as to be globally applicable, or it may instead deem the framework inappropriate for some scenarios and mean that separate approaches are required for use in different regions or require adjustments to be made to the framework.

Performance monitoring and impact evaluation are deemed essential in determining whether NbS effectively respond to the challenges to which they are being applied (Dumitru & Wendling, 2021), and in their recommendations for operationalising NbS in response to natural hazards, Kumar et al. (2020) highlight the importance of obtaining demonstrable evidence of NbS in the field. They suggest that NbS performance should be measured against multiple metrics to prove concepts and encourage their uptake, and advocate that this be conducted through the use of OALs. The lack of scientific and grey literature on NbS as CCA measures in the rail context reinforces the need, and strengthens the recommendation for the industry to conduct, write up and share research on OALs or pilot sites to fill the void (or procure consultancy services and/or sponsor academic research to do so). The trialling of NbS concepts in rail OALs would allow the practical evaluation of the processes proposed in the operationalisation of NbS for rail CCA framework, enabling an assessment of the validity and effectiveness of the recommended steps under real world conditions, and the identification of any further refinements or enhancements that should be made to the tool.

Extensive in situ testing would also generate the much-needed performance data to evidence NbS performance in the rail environment to prove their suitability and success (or otherwise), and enable lessons learned and best practices to be gathered and shared across the industry, whilst also facilitating the continual improvement of the NbS framework. The monitoring and impact evaluation of NbS can include the use of biophysical, socio-economic and sustainability indicators of NbS performance and impact which are targeted to assess specific characteristics of NbS effectiveness (Dumitru & Wendling, 2021). Dumitru & Wendling provide a number of recommendations to support the development and implementation of robust monitoring and evaluation plans for NbS impact evaluations (2021), which could be applied to rail OALs and to the longer term monitoring and evaluation of NbS performance during the 'Operation & Maintenance' phase of the rail and NbS intervention lifecycles, as per Figure 5-4. This research recommends a number of specific criteria against which NbS performance could be measured and monitored in rail OALs, using Key Performance Indicators (KPI) which will also help to inform future cost benefit analyses and CCA option selection, including the comparison against grey engineered measures. Examples of relevant KPI metrics that may be applied to the monitoring and evaluation of NbS performance in the rail environment are provided in Table 6-2.

Further rail-specific KPIs that could be applied include rail temperature (Network Rail, 2024a) (in ° C, as an indicator of climate resilience) and passenger delay minutes (Office of Road and Rail, 2023) (in minutes, as an indicator of natural and climate hazards and social impact). It is also recommended that rail OALs include stakeholder involvement from landowners and communities that neighbour railway infrastructure, to gather their input and support to establish NbS interventions, and provide opportunities for landscape-scale features that deliver greater cumulative ecosystem services to the wider environs. This outreach should involve the academic community, as discussed in the following section. The testing of NbS under controlled rail environments, such as OALs, could support the 'type approval' (Rail Industry Safety Standards Board Ltd., 2023) and 'product acceptance' (Network Rail, 2023) processes that are typically required by rail organisations to introduce new materials and/or practices to safety critical rail infrastructure.

Table 6-2 Potential key performance indicators that may be used to monitor and evaluate NbS effectiveness in the rail context (from Dumitru & Wendling, 2021)

Societal challenge area	Key Performance Indicator	Units
Climate resilience	Urban heat island incidence	Number of days
	Soil temperature	° C
Water management	Surface runoff in relation to precipitation quantity	mm/%
Natural and climate hazards	Mean annual direct and indirect losses due to natural and climate hazards	$
	Railways exposed to risk	m/km
Biodiversity	Species diversity within a defined area	Number
	Area of habitats restored	Ha
Participatory planning	Stakeholder involvement in co-creation/ co-design of NBS	Number
Economic opportunities	NBS cost/benefit analysis	Payback period year

As discussed in Chapter 3, it is anticipated that hybrid, grey-green options may be more appropriate for, and acceptable to, the rail industry in the first instance, to aid the phase in of a 'new' concept, combined with the fact that NbS may not deliver sufficient CCA capability on their own, meaning that NbS are used to complement more robust grey solutions. OALs could be used to test the most effective grey-green or 'hybrid' composition for rail CCA solutions. Additional factors that could be examined in OAL are variables suggested earlier in this study that may impact NbS performance and suitability, including the application of NbS concepts in rural versus urban settings, and implementation of the framework on new infrastructure as opposed to the retrofit of existing assets.

Chapter 3 proposes the CCRA process as the key entry point for CCA, and consequently NbS, into the management of rail infrastructure. The undertaking of CCRA is not only significant to the operationalisation of NbS, but critical to the identification, analysis and evaluation of the risks posed to rail infrastructure by climate change and the onward selection of risk reduction measures, including CCA responses such as NbS. Chapter 4 reveals, however, that almost one in four rail infrastructure projects do not undertake CCRA, which represents a considerable blocker to the incorporation of vital CCA measures into rail infrastructure, and subsequently a barrier to the uptake of NbS. With the United Nations confirming that "groundbreaking acceleration" is urgently required in regards CCA planning and implementation (United Nations Environment Programme, 2022, p. xiii), it is therefore recommended that the requirement for CCRA to be undertaken is mandated, globally, for all projects to build new, and enhance existing, rail infrastructure. As echoed by the questionnaire responses from rail professionals cited in Chapter 4, this mandate could be directed through industry policy, standards and client specification, as these mechanisms have been deemed by those surveyed as being the top tool to aid the roll out of NbS in the industry. A further recommendation to instil climate risk into the management of rail infrastructure is through promotion of the use of sustainability benchmarking schemes, e.g., Building Research Establishment (2021), Infrastructure Sustainability Council (2021b), to drive continuous improvement and the use of innovative solutions, including green infrastructure. In many jurisdictions the use of sustainability benchmarking schemes, and in some instances the attainment of minimum rating scores, is mandated for the planning, design and construction of significant rail infrastructure, e.g., Infrastructure Sustainability Council (2023);

introducing this requirement for rail infrastructure projects would therefore present a means of encouraging the uptake of NbS for CCA.

Whilst the figures and frameworks in Chapters 2, 3 and Chapter 5 provide tools for direct use by the rail industry, the primary data outputs of Chapter 4 offer an excellent point of reference to help inform future work to be undertaken by the rail industry. Although subject to the limitations outlined in the previous section, the questionnaire responses obtained through this research provide valuable insights from 55 rail industry professionals which can be used to influence and help prioritise industry action, including further research on CCA, and specifically the use of NbS for this purpose, on rail infrastructure. For example, the industry may use this data to focus on the top barriers to NbS implementation for CCA (Lack of NbS awareness, Rail resistance to change – see Table 4-2) or the top enablers (Policy & Standards, Client Specifications – see Table 4-3).

The recommendation to consider railway and climate analogues is highlighted throughout this research. This approach will support learning and sharing between and across countries that are and/or will be subjected to similar HMH. As highlighted above, the rail industry should direct more attention to and cooperation with rail infrastructure owners in the global South. These collaborative efforts (e.g., working groups) and communications (e.g., rail NbS case study libraries) could be coordinated by national and international rail bodies, such as the Association of American Railroads (2023) and the International Union of Railways (2023b). These organisations could also lead the rail sector's participation in cross-industry liaison with other domains e.g., telecommunications and electricity, to support the development of joined up, mutually beneficial NbS that can protect multiple assets and infrastructure from the impacts of climate change. These connections could be extended to other linear infrastructure e.g., highways, working with agencies such as the World Road Association (PIARC, 2023) and the International Road Federation (2023).

A rudimentary review of the literature on the highway industry's use of NbS for CCA reveals that some case studies have been prepared on the implementation of NbS concepts on roads in response to HMH causing landslides, flooding and water-induced erosion and scour, e.g., 'Slope Protection Using Deep-Root Vegetative Solution' and 'Use of Bioengineering for Slope Stabilisation' (Asociación Mundial de la Carretera, 2022). Additionally, the US Department of Transportation's Federal Highway Administration have prepared an implementation guide on the use of NbS for coastal highway resilience (2019). The guide details engineering and ecological design factors, pitched at transportation professionals, to inform their consideration of NbS in the protection of coastal highways as part of a wider array, or combination, of resilience measures. The guidance includes technical factsheets on six NbS concepts: Marsh Vegetation, Marsh Breakwater, Marsh Sill, Beach Nourishment, Pocket Beach and Dune Restoration; these concepts generally align with the 'Dune/Beach restoration' and 'Salt marshes' solutions as proposed in this study for use on rail infrastructure. The factsheets provide an overview and case study example of the application of each technique (US Department of Transportation, 2019). It is recommended that similar material be prepared for the application of each NbS concept suggested for use on rail infrastructure, using outputs from previously suggested rail NbS OALs.

6.4 Outlook and way forward – research

A key output from this study is the framework for use by the railway sector to operationalise NbS as CCA measures for rail infrastructure. Whilst mainly directed to a rail audience, it is hoped that this study, and its content published in peer-reviewed journals, pique interest from academia and inspires further scientific research on this topic. The pressing need for rail infrastructure to be protected from and adapted to accommodate the impacts of a changing climate, and the current gaps in rail CCA both in research and in practice, are reiterated throughout this research. This confirms the urgent need for, and provides a compelling call to action to climate scientists to support the rail industry in protecting and adapting its critical infrastructure. The United Nations make multiple references to this study's first paper (Chapter 2) in their publication 'Nature-based Infrastructure: How natural infrastructure solutions can address sustainable development challenges and the triple planetary crisis' (United Nations Environment Programme, 2023). Their report highlights examples and recommendations from this research concerning the use of NbS to protect railway networks from climate impacts. Recognition of this work by this high-profile global organisation, combined with its coverage in mainstream media outlets (Bloomberg, 2024; Der Spiegel, 2022; Inside Climate News, 2022) will hopefully help to further promote and prompt further research on the use of NbS for CCA on rail infrastructure.

Throughout all four research papers, and as included as a key step in the framework to operationalise NbS as CCA for rail, the need to increase awareness and provide education to the rail industry on NbS, and more broadly, the general need for CCA and the undertaking of CCRA are advocated. Academics can play a key role in developing, and potentially delivering, the materials to fulfil this need. Research communities can also support the establishment and scientific governance of rail OALs. For example, noting the wide range of scientific expertise required to effectively monitor and evaluate the many facets of NbS performance (Raymond et al., 2017), Dumitru & Wendling (2021) recommend collaboration with universities (and other professionals with scientific knowledge and experience) to support these activities. The global extent of the rail network means there are widespread opportunities to collate data on the use and success (or otherwise) of NbS implementation. As discussed in the preceding sections, it is recommended that follow up research focusses on the global South as a priority, where reporting on the general ecological characteristics of NbS has already been found to be particularly lacking, potentially due to the economic, technological and labour requirements required to make robust performance evaluations (Key et al., 2022). The resources and expertise required for these types of study are often more difficult to source in the global South (Sietsma et al., 2021), meanwhile inequalities in the distribution of research funding has been found to align with the poor representation of NbS research in lower income countries (Woroniecki et al., 2023). The NbS research gap between the global North and South extends to NbS research scope as well as its quantity (Sietsma et al., 2021), which emphasises the need for financial backing to be provided to support research in lower income regions.

The outputs of the trial and any subsequent use of NbS concepts on rail infrastructure may be transferable to other applications. The applicability of the processes outlined in Figure 5-4 could therefore be examined to assess whether they could potentially deliver CCA for other industries and scenarios. Further scientific testing of the framework's implementation of NbS as CCA for rail may therefore contribute to the wider bodies of research on CCA, the selection of CCA options (grey, NbS and/or hybrid), and the operationalisation of NbS, including the development of practical measures to aid their deployment.

Regarding the wider dissemination of NbS, the IUCN Global Standard for NbS, supported by the principles for successful NbS implementation and upscaling (Cohen-Shacham et al., 2019; Cohen-Shacham et al., 2016), has been launched as a vehicle to aid their design and verification, to deliver the desired outcomes in response to societal challenge(s), including CCA (IUCN, 2020). The Standard, which provides a self-assessment tool against which users can establish adherence to the IUCN NbS criteria, claims to enable "the translation of the NbS concepts into targeted actions from implementation" (IUCN, 2020, p. 4). Although the Standard provides a consistent mechanism for approaching, and a common language for engagement on, NbS implementation, which will facilitate learning on and evolution of NbS deployment, it (intentionally) does not stipulate prescriptive specifications for NbS; the provision of detailed stipulations has previously been identified as a specific gap for rail CCA interventions (Armstrong et al., 2017). A benefit of the Global Standard is that it may be used alongside other tools and practices, however, and it could therefore be applied to an NbS intervention that is developed also using the framework provided in this research. The relevance of this research is assessed against the Global Standard for NbS and the principles upon which the Global Standard is based, and the alignment (or otherwise) of the proposed framework for NbS implementation as CCA for rail with these instruments is summarised in Appendix G. The use of these complementary mechanisms for NbS implementation would help to provide credibility that a rail intervention has been designed and installed to a robust, recognised Standard, meanwhile learning gained through use of the rail Framework could be fed into the growing body of conservation science being collated by the IUCN and add to engagement and dialogue on NbS. The IUCN governance structure for the Global Standard (2020, p. 5) includes national or regional "Operationalising hubs" however its International Standard Committee may also wish to consider the establishment of community of practice hubs by sector (to include rail). This would enable cross-regional and international NbS practitioners and scientists to engage and collaborate on and improve NbS interventions for the sector, meanwhile their access to regional and/or national hubs for more general NbS users would allow cross-industry sharing and facilitate opportunities to engage with climate analogues.

It is recommended that when publishing study outputs, researchers take heed of the weaknesses in pilot case studies flagged by the European Commission (2018). As previously discussed, railway employees are not climatology experts (Quinn et al., 2017); this works both ways. Just as non-scientific language has been used in the rail industry audience case studies [Appendices D, E and F], this study, and in particular the introduction to climate change impacts on the various components of rail infrastructure provided in the tables and figures of Chapter 2, is intended to be accessible to the research community. This study has introduced and applied rail infrastructure terminologies to the CCA and NbS literature, and it has highlighted multiple knowledge gaps and confirmed both the need and demand for further scientific research on these topics within the rail industry. This research therefore opens the door to, and makes the case for, further CCA and NbS research in and with the rail sector in response to the growing risk to the industry's infrastructure posed by climate change, with a view to advancing a collaborative response to the societal challenge posed by climate change impacts on rail infrastructure.

Appendices

Appendix A Supplementary text S1 (Chapter 2)

Table 1 Literature review search terms and strings applied

	Search category		
	NbS	**CCA**	**Railway Infrastructure**
Key words	• nature-based solutions • nature based solutions • NbS • green infrastructure • blue green infrastructure • green blue infrastructure • ecological engineering • ecosystem-based adaptation • ecosystem based adaptation • EbA • natural infrastructure • ecosystem-based disaster risk reduction • Eco-DRR • ecosystem services • climate adaptation services	• climate change adaptation • climate adaptation	• rail • railway • rail infrastructure • railway infrastructure • railroad • railway track
Scopus and Science Direct search string	TITLE-ABS-KEY((“nature-based solutions” OR “nature based solutions” OR NBS OR NbS OR “green infrastructure” OR “blue green infrastructure” OR “green blue infrastructure” OR “ecological engineering” OR “ecosystem-based adaptation” OR “ecosystem based adaptation” OR EbA OR “natural infrastructure” OR “ecosystem-based disaster risk reduction” OR “Eco-DRR” OR “ecosystem services” OR “climate adaptation services”) AND (“climate change adaptation” OR “climate adaptation”) AND (rail OR railway OR “rail infrastructure” OR “railway infrastructure” OR railroad OR “railway track”))		
Web of Science search string	TI = (("nature-based solutions" OR "nature based solutions" OR NBS OR NbS OR "green infrastructure" OR "blue green infrastructure" OR "green blue infrastructure" OR "ecological engineering" OR "ecosystem-based adaptation" OR "ecosystem based adaptation" OR EbA OR "natural infrastructure" OR "ecosystem-based disaster risk reduction" OR "ecosystem services" OR "climate adaptation services") AND ("climate change adaptation" OR "climate adaptation") AND (rail OR railway OR "rail infrastructure" OR "railway infrastructure" OR railroad OR "railway track")) OR AB = (("nature-based solutions" OR "nature based solutions" OR NBS OR NbS OR "green infrastructure" OR "blue green infrastructure" OR "green blue infrastructure" OR "ecological engineering" OR "ecosystem-based adaptation" OR "ecosystem based adaptation" OR EbA OR "natural infrastructure" OR "ecosystem-based disaster risk reduction" OR “Eco-DRR” OR "ecosystem services" OR "climate adaptation services") AND ("climate change adaptation" OR "climate adaptation") AND (rail OR railway OR "rail infrastructure" OR "railway infrastructure" OR railroad OR "railway track")) OR AK = (("nature-based solutions" OR "nature based solutions" OR NBS OR NbS OR "green infrastructure" OR "blue green infrastructure" OR "green blue infrastructure" OR "ecological engineering" OR "ecosystem-based adaptation" OR "ecosystem		

	Search category		
	NbS	**CCA**	**Railway Infrastructure**
	based adaptation" OR EbA OR "natural infrastructure" OR "ecosystem-based disaster risk reduction" OR "ecosystem services" OR "climate adaptation services") AND ("climate change adaptation" OR "climate adaptation") AND (rail OR railway OR "rail infrastructure" OR "railway infrastructure" OR railroad OR "railway track")) OR KP = (("nature-based solutions" OR "nature based solutions" OR NBS OR NbS OR "green infrastructure" OR "blue green infrastructure" OR "green blue infrastructure" OR "ecological engineering" OR "ecosystem-based adaptation" OR "ecosystem based adaptation" OR EbA OR "natural infrastructure" OR "ecosystem-based disaster risk reduction" OR "ecosystem services" OR "climate adaptation services") AND ("climate change adaptation" OR "climate adaptation") AND (rail OR railway OR "rail infrastructure" OR "railway infrastructure" OR railroad OR "railway track"))		

Searches in these scientific databases resulted in one article (Figure 1). Some applicable literature might have been inadvertently eliminated from the review due to the search string adopted and/or the language of publication.

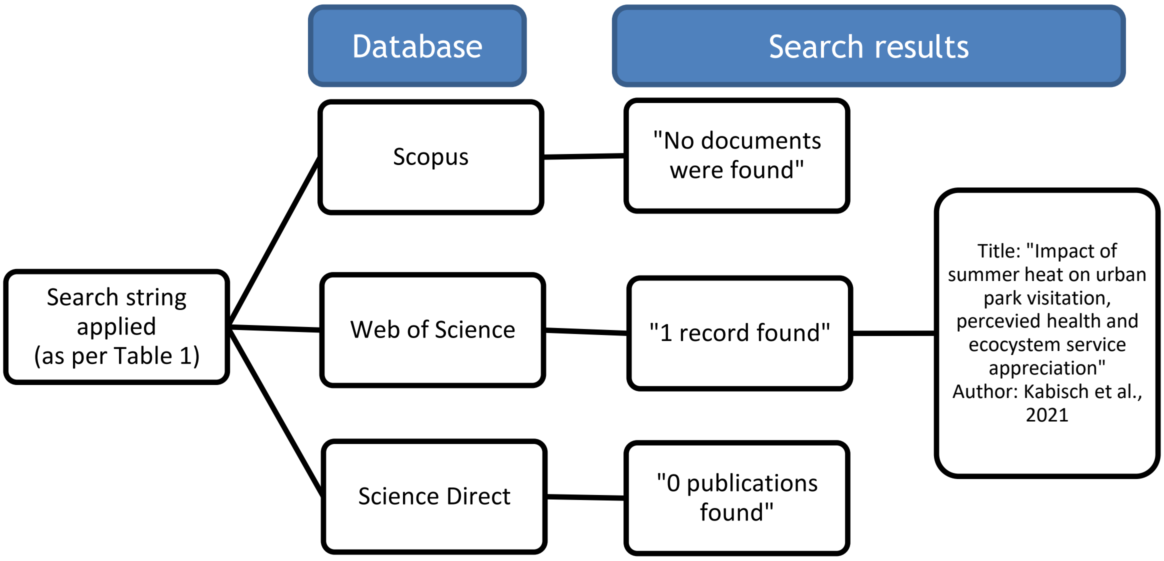

Figure 1 Search methods and outputs

Appendix B Supplementary text S1 (Chapter 4)

University of Glasgow

College of Social Sciences

Nature-based Solutions as climate change adaptation measures for rail

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Participant Information

You are being invited to take part in a research study. Before you decide to take part it is important for you to understand why the research is being carried out and what it will involve. Please read the following information carefully. Ask the researcher if there is anything that is not clear or if you would like more information. Thank you for reading this.

Railways are very exposed and vulnerable to extreme weather, with climate-related risks expected to increase and worsen, it is vitally important to understand how rail infrastructure should be adapted to withstand the pressures of current and future predicted climate change. Measures for adapting to climate change can incorporate a range of potential actions including engineered interventions (e.g. sea walls and levees) and management approaches (e.g. early warning systems for extreme weather). There is growing recognition that 'nature-based solutions' may be used as climate change adaptation measures to reduce the risks posed by climate change, whilst also providing biodiversity and human well-being benefits. Nature-based solutions can be blended with traditional engineered systems to provide hybrid climate change adaptation options.

The aim of this research is to understand rail industry awareness on, and interest in the use of nature-based solutions as climate change adaptation measures for railway infrastructure. As a rail industry professional, your experience, knowledge and thoughts in relation to these issues are very much appreciated.

The survey time varies but it is designed to last on average 20 minutes. Your participation in the questionnaire is voluntary. No data will be attributed to you as an individual. In other words, the questionnaire will be anonymous. Confidentiality will be respected subject to legal constraints and professional guidelines.

The resulting data will be stored electronically in a password protected location on a secure server. Data will be used by the researcher for writing journal articles and for conferences and will only be shared as anonymous data with other trusted research institutions on request. Data will be kept for 10 years after publication and then securely disposed of.

If you have any questions on this research please contact the researcher: l.blackwood.2@research.gla.ac.uk

Results from the research, in the form of written summaries or final manuscripts, will be provided upon request to the researcher: l.blackwood.2@research.gla.ac.uk

To pursue any complaint about the conduct of the research contact the College of Social Sciences Lead for Ethical Review, Dr Susan Batchelor socsci-ethics-lead@glasgow.ac.uk

Privacy Notice

Privacy Notice for Participation in Research Project

Your Personal Data

The University of Glasgow will be what's known as the 'Data Controller' of your personal data processed in relation to your participation in the research project 'The use of nature-based solutions as climate change adaptation measures for rail'. This privacy notice will explain how The University of Glasgow will process your personal data.

Why we need it

We are collecting basic personal data such as your job title and geographic location in order to conduct our research. We need these details to help analyse and interpret responses which are being collated globally.

We only collect data that we need for the research project and will de-identify your personal data from the research data by using pseudonyms. Any responses which contain information that may enable you to be identified will be redacted before the data is analysed. Please see the accompanying **Participant Information**.

Legal basis for processing your data

We must have a legal basis for processing all personal data. As this processing is for Academic Research, we will be relying upon the basis of the General Data Protection Regulation's (GDPR) **Task in the Public Interest** category to process the basic personal data that you provide. For any special categories data collected we will be processing this on the basis that it is **necessary for archiving purposes, scientific or historical research purposes or statistical purposes**

Alongside this, in order to fulfil our ethical obligations, we will ask for your **Consent** to take part in the study. Please see the accompanying **Participant Consent Form**.

What we do with it and who we share it with

The personal data you submit will be processed by: Lorraine Blackwood (Postgraduate Researcher), Professor Fabrice Renaud and Dr Steven Gillespie at the University of Glasgow in the United Kingdom. In addition, security measures are in place to ensure that your personal data remains safe: data will be stored on University of Glasgow electronic files which are data encrypted and available by password only. Please consult the **Participant Consent Form** and **Participant Information** which accompany this notice.

We will provide you with a copy of the study findings and details of any subsequent publications or outputs on request. Anonymised datasets will be openly available via the University of Glasgow's 'Enlighten' data repository and from the researcher by personal request.

What are your rights?

GDPR provides that individuals have certain rights including: to request access to, copies of and rectification or erasure of personal data and to object to processing. In addition, data subjects may also have the right to restrict the processing of the personal data and to data portability. You can request access to the information we process about you at any time.

If at any point you believe that the information we process relating to you is incorrect, you can request to see this information and may in some instances request to have it restricted, corrected, or erased. You may also have the right to object to the processing of data and the right to data portability.

Please note that as we are processing your personal data for research purposes, the ability to exercise these rights may vary as there are potentially applicable research exemptions under the GDPR and the Data Protection Act 2018. For more information on these exemptions, please see UofG Research with personal and special categories of data.

If you wish to exercise any of these rights, please submit your request via the webform or contact dp@gla.ac.uk

Complaints

If you wish to raise a complaint on how we have handled your personal data, you can contact the University Data Protection Officer who will investigate the matter.

Our Data Protection Officer can be contacted at dataprotectionofficer@glasgow.ac.uk

If you are not satisfied with our response or believe we are not processing your personal data in accordance with the law, you can complain to the Information Commissioner's Office (ICO) https://ico.org.uk/

Who has ethically reviewed the project?

This project has been ethically approved via the College of Social Sciences Research Ethics Committee.

How long do we keep it for?

Your **personal** data will be retained by the University only for as long as is necessary for processing and no longer than the period of ethical approval which ends on 30th June 2024. After this time, personal data will be securely deleted.

Your **research** data will be retained for a period of ten years in line with the University of Glasgow Guidelines. Specific details in relation to research data storage are provided on the Participant Information Sheet and Consent Form which accompany this notice.

Participant Consent Form

I confirm that I have read and understood the Participant Information (previous page) for the above study and have had the opportunity to ask questions. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason.

• I understand that responses to this questionnaire will be used as research data for the above project.

• All surveys are anonymous.

• The data will be treated as confidential and kept in secure storage at all times.

• The data will be destroyed 10 years after the project is complete and only shared as anonymous material upon request with trusted research institutions.

• The data may be used in future publications, both print and online, and in conference proceedings.

• I agree to waive my copyright to any data collected as part of this project.

Please select as appropriate: *Required*

(•) I agree to take part in this research study

( ) I do not agree to take part in this research study

Question 1

How often does your organisation carry out climate change risk assessments during the planning, design, construction and/or operation of new or when making upgrades to existing railway infrastructure (and/or how often does your organisation require other parties to carry out climate change risk assessments)?

( ) Never

( ) Rarely

( ) Sometimes

( ) Often

- Always

Are you involved in carrying out climate change risk assessments?

- Yes
- No

Question 2

Which rail infrastructure lifecycle stage(s) have climate change risk assessments covered? Please select all that apply.

- [ ] Planning
- [ ] Design
- [ ] Construction
- [ ] Operation
- [ ] Maintenance/Renewal/Enhancement
- [ ] Decommissioning
- [ ] I don't know

Which rail discipline(s) have the climate change risk assessments covered? Please select all that apply.

- [ ] Track
- [ ] Signalling
- [ ] Overhead Wiring
- [ ] Civils
- [ ] Structures
- [ ] Electrical
- [ ] Telecommunications
- [ ] Maintenance and/or Stabling Yards
- [ ] Stations, Signal Boxes and/or other railway buildings
- [ ] I don't know

☐ Other

If you selected Other, please specify:

Which climate hazards have the climate change risk assessments covered? Please select all that apply.

☐ High temperatures

☐ Low temperatures

☐ High precipitation

☐ Low precipitation

☐ High winds

☐ High sea levels and storm surges

☐ Lightning & electrical storms

☐ I don't know

☐ Other

If you selected Other, please specify:

Question 3

Are you aware of climate change adaptation options for rail infrastructure?

○ Yes

○ No

Question 4

The next questions will ask how familiar you are with a selection of "nature-based solutions". You will be asked to rate your level of familiarity using the following scale:

0 – I have never heard of this concept

1 – I am aware of this concept

2 – I am aware of this concept being used on rail infrastructure

3 – I have been involved in using this concept on rail infrastructure

When considering your response please include any hybrid options which combine nature-based solutions with traditional engineered adaptation measures.

Use of vegetation to protect assets/infrastructure

How familiar are you with the use of vegetation to protect assets/infrastructure (for example by providing shade or wind shelter)?

- 0 – I have never heard of this concept
- 1 – I am aware of this concept
- 2 – I am aware of this concept being used on rail infrastructure
- 3 – I have been involved in using this concept on rail infrastructure

At what location(s) are you aware of vegetation being used to protect railway assets/infrastructure? Please provide the location, including the country, for each example.

Vegetation was used to protect railway assets/infrastructure in response to which climate change hazard(s)? Please select all that apply.

- High temperatures
- Low temperatures
- High winds
- High sea levels and storm surges
- High precipitation
- Lightning & electrical storms
- Low precipitation
- I don't know
- Other

If you selected Other, please specify:

How well do you feel the use of vegetation to protect railway assets/infrastructure has performed as a climate change adaptation measure?

- 1 Highly effective

- 2 Partly effective
- 3 Partly ineffective
- 4 Highly ineffective
- I don't know

Please describe any problems that you are aware of being encountered in using vegetation to protect railway assets/infrastructure

Please describe any additional benefits that you are aware of being gained through using vegetation to protect railway assets/infrastructure

Please share any learning points you are aware of being obtained through using vegetation to protect railway assets/infrastructure

Green corridors

How familiar are you with the use of green corridors?

- 0 – I have never heard of this concept
- 1 – I am aware of this concept
- 2 – I am aware of this concept being used on rail infrastructure
- 3 – I have been involved in using this concept on rail infrastructure

At what location(s) are you aware of green corridors being used on rail infrastructure? Please provide the location, including the country, for each example.

Green corridors were used on rail infrastructure in response to which climate change hazard(s)? Please select all that apply.

- High temperatures

- Low temperatures
- High winds
- High sea levels and storm surges
- High precipitation
- Lightning & electrical storms
- Low precipitation
- I don't know
- Other

If you selected Other, please specify:

How well do you feel green corridors have performed as a climate change adaptation measure for rail infrastructure?

- 1 Highly effective
- 2 Partly effective
- 3 Partly ineffective
- 4 Highly ineffective
- I don't know

Please describe any problems you are aware of being encountered in using green corridors on rail infrastructure

Please describe any additional benefits you are aware of being gained through using green corridors on rail infrastructure

Please share any learning points you are aware of being obtained through using green corridors on rail infrastructure

Natural drainage solutions

How familiar are you with the use of natural drainage solutions, for example Sustainable Urban Drainage Systems (SUDS) or Water Sensitive Urban Drainage (WSUD)?

- 0 – I have never heard of this concept
- 1 – I am aware of this concept
- 2 – I am aware of this concept being used on rail infrastructure
- 3 – I have been involved in using this concept on rail infrastructure

At what location(s) are you aware of natural drainage solutions being used on rail infrastructure? Please provide the location, including the country, for each example.

Natural drainage solutions were applied on rail infrastructure in response to which climate change hazard(s)? Please select all that apply.

- High temperatures
- Low temperatures
- High winds
- High sea levels and storm surges
- High precipitation
- Lightning & electrical storms
- Low precipitation
- I don't know
- Other

If you selected Other, please specify:

How well do you feel natural drainage solutions have performed as a climate change adaptation measure for rail infrastructure?

- 1 Highly effective
- 2 Partly effective
- 3 Partly ineffective
- 4 Highly ineffective
- I don't know

Please describe any problems that you are aware of being encountered in using natural drainage solutions on rail infrastructure

Please describe any additional benefits that you are aware of being gained through using natural drainage solutions on rail infrastructure

Please share any learning points that you are aware of being obtained through using natural drainage solutions on rail infrastructure

Bioengineering and biotechnical stabilisation

How familiar are you with bioengineering and/or biotechnical stabilisation?

- 0 – I have never heard of this concept
- 1 – I am aware of this concept
- 2 – I am aware of this concept being used on rail infrastructure
- 3 – I have been involved in using this concept on rail infrastructure

At what location(s) are you aware of bioengineering and/or biotechnical stabilisation being used on rail infrsatructure? Please provide the location, including the country, for each example.

Bioengineering and/or biotechnical stabilisation was applied on rail infrastructure in response to which climate change hazard(s)? Please select all that apply.

- [ ] High temperatures
- [ ] Low temperatures
- [ ] High winds
- [ ] High sea levels and storm surges
- [ ] High precipitation
- [ ] Lightning & electrical storms
- [ ] Low precipitation
- [ ] I don't know
- [ ] Other

If you selected Other, please specify:

How well do you feel bioengineering and/or biotechnical stabilisation performed as a climate change adaptation measure on rail infrastructure?

- ○ 1 Highly effective
- ○ 2 Partly effective
- ○ 3 Partly ineffective
- ○ 4 Highly ineffective
- ○ I don't know

Please describe any problems that you are aware of being encountered in using bioengineering and/or biotechnical stabilisation on rail infrastructure

Please describe any additional benefits that you are aware of being gained through the use of bioengineering and/or biotechnical stabilisation on rail infrastructure

Please share any learning points that you are aware of being obtained through the use of bioengineering and/or biotechnical stabilisation on rail infrastructure

Green walls and embankments

How familiar are you with the use of green walls and/or embankments?

- 0 – I have never heard of this concept
- 1 – I am aware of this concept
- 2 – I am aware of this concept being used on rail infrastructure
- 3 – I have been involved in using this concept on rail infrastructure

At what location(s) are you aware of green walls and/or embankments being used on rail infrastructure? Please provide the location, including the country, for each example.

Green walls and/or embankments were applied on rail infrastructure in response to which climate change hazard(s)? Please select all that apply.

- High temperatures
- Low temperatures
- High winds
- High sea levels and storm surges
- High precipitation
- Lightning & electrical storms
- Low precipitation
- I don't know
- Other

If you selected Other, please specify:

How well do you feel green walls and/or embankments performed as a climate change adaptation measure for rail infrastructure?

- 1 Highly effective
- 2 Partly effective
- 3 Partly ineffective
- 4 Highly ineffective
- I don't know

Please describe any problems that you are aware of being encountered in using green walls and/or embankments on rail infrastructure

Please describe any additional benefits that you are aware of being gained through using green walls and/or embankments on rail infrastructure

Please share any learning points that you are aware of being obtained from the use of green walls and/or embankments on rail infrastructure

Protection forests

How familiar are you with the use of protection forests to mitigate or prevent the impact of natural hazards (e.g. rockfall, avalanche, erosion, landslide)?

- 0 – I have never heard of this concept
- 1 – I am aware of this concept
- 2 – I am aware of this concept being used on rail infrastructure
- 3 – I have been involved in using this concept on rail infrastructure

At what location(s) are you aware of protection forests being used to protect rail infrastructure? Please provide the location, including the country, for each example.

Protection forests were applied on rail infrastructure in response to which climate change hazard(s)? Please select all that apply.

- High temperatures
- Low temperatures
- High winds
- High sea levels and storm surges
- High precipitation
- Lightning & electrical storms
- Low precipitation
- I don't know
- Other

If you selected Other, please specify:

How well do you feel protection forests performed as a climate change adaptation measure for rail infrastructure?

- 1 Highly effective
- 2 Partly effective
- 3 Partly ineffective
- 4 Highly ineffective
- I don't know

Please describe any problems that you are aware of being encountered using protection forests on rail infrastructure

Please describe any additional benefits you are aware of being gained through using protection forests on rail infrastructure

Please share any learning points you are aware of being obtained through using protection forests on rail infrastructure

Selection of specific plant species and vegetation types

How familiar are you with particular plant species and/or vegetation types being selected in order to provide climate change adaptation benefits?

- 0 – I have never heard of this concept
- 1 – I am aware of this concept
- 2 – I am aware of this concept being used on rail infrastructure
- 3 – I have been involved in using this concept on rail infrastructure

At what location(s) are you aware of particular plant species and/or vegetation types been used on rail infrastructure to provide climate change adaptation benefits? Please provide the location, including the country, for each example.

Particular plant species and/or vegetation types were used on rail infrastructure to provide climate change adaptation benefits in response to which climate change hazard(s)? Please select all that apply.

- High temperatures
- Low temperatures
- High winds
- High sea levels and storm surges
- High precipitation
- Lightning & electrical storms
- Low precipitation
- I don't know
- Other

If you selected Other, please specify:

How well do you feel the use of particular plant species and/or vegetation types on rail infrastructure to provide climate change adaptation benefits performed?

- 1 Highly effective
- 2 Partly effective
- 3 Partly ineffective
- 4 Highly ineffective
- I don't know

Please describe any problems that you are aware of being encountered in using particular plant species and/or vegetation types to provide climate change adaptation benefits for rail infrastructure

Please describe any additional benefits that you are aware of being gained through using particular plant species and/or vegetation types to provide climate change adaptation benefits for rail infrastructure

Please share any learning points you are aware of being obtained through using particular plant species and/or vegetation types to provide climate change adaptation benefits for rail infrastructure

Dune and beach restoration

How familiar are you with the use of dune and/or beach restoration to protect coastal infrastructure?

- 0 – I have never heard of this concept
- 1 – I am aware of this concept
- 2 – I am aware of this concept being used on rail infrastructure
- 3 – I have been involved in using this concept on rail infrastructure

At what location(s) are you aware of dune and/or beach restoration being used to protect coastal rail infrastructure? Please provide the location, including the country, for each example.

Dune and/or beach restoration has been used on rail infrastructure in response to which climate change hazard(s)? Please select all that apply.

Please select at least 1 answer(s).

- [ ] High temperatures
- [ ] Low temperatures
- [ ] High winds
- [ ] High sea levels and storm surges
- [ ] High precipitation
- [ ] Lightning & electrical storms
- [ ] Low precipitation
- [ ] I don't know
- [ ] Other

If you selected Other, please specify:

How well do you feel the use of dune and/or beach restoration has performed as a climate change adaptation measure for rail infrastructure ?

- ○ 1 Highly effective
- ○ 2 Partly effective
- ○ 3 Partly ineffective
- ○ 4 Highly ineffective
- ○ I don't know

Please describe any problems that you are aware of being encountered in using dune and/or beach restoration to protect coastal rail infrastructure

Please describe any additional benefits that you are aware of being gained through the use of dune and/or beach restoration to protect coastal rail infrastructure

Please share any learning points that you are aware of being obtained through the use of dune and/or beach restoration to protect coastal rail infrastructure

Salt marshes

How familiar are you with the use of salt marshes to protect coastal infrastructure?

- 0 – I have never heard of this concept
- 1 – I am aware of this concept
- 2 – I am aware of this concept being used on rail infrastructure
- 3 – I have been involved in using this concept on rail infrastructure

At what location(s) are you aware of salt marshes being used to protect coastal rail infrastructure? Please provide the location, including the country, for each example.

Salt marshes were used on rail infrastructure in response to which climate change hazard(s)? Please select all that apply.

- High temperatures
- Low temperatures
- High winds
- High sea levels and storm surges
- High precipitation
- Lightning & electrical storms
- Low precipitation
- I don't know
- Other

If you selected Other, please specify:

How well do you feel salt marshes have performed as a climate change adaptation measure for rail infrastructure?

- 1 Highly effective
- 2 Partly effective
- 3 Partly ineffective
- 4 Highly ineffective
- I don't know

Please describe any problems that you are aware of being encountered in using salt marshes to protect coastal rail infrastructure

Please describe any additional benefits that you are aware of being gained through using salt marshes to protect coastal rail infrastructure

Please share any learning points that you are aware of being obtained through using salt marshes to protect coastal rail infrastructure

Reefs and mangroves

How familiar are you with the use of reefs and/or mangroves to protect coastal infrastructure?

- 0 – I have never heard of this concept
- 1 – I am aware of this concept
- 2 – I am aware of this concept being used on rail infrastructure
- 3 – I have been involved in using this concept on rail infrastructure

At what location(s) are you aware of reefs and/or mangroves being used to protect coastal rail infrastructure? Please provide the location, including the country, for each example.

Reefs and/or mangroves were used on rail infrastructure in response to which climate change hazard(s)? Please select all that apply.

- [ ] High temperatures
- [ ] Low temperatures
- [ ] High winds
- [ ] High sea levels and storm surges
- [ ] High precipitation
- [ ] Lightning & electrical storms
- [ ] Low precipitation
- [ ] I don't know
- [ ] Other

If you selected Other, please specify:

How well do you feel reefs and/or mangroves have performed as a climate change adaptation measure for rail infrastructure?

- ○ 1 Highly effective
- ○ 2 Partly effective
- ○ 3 Partly ineffective
- ○ 4 Highly ineffective
- ○ I don't know

Please describe any problems that you are aware of being encountered in using reefs and/or mangroves to protect coastal rail infrastructure

Please describe any additional benefits that you are aware of being gained through using reefs and/or mangroves to protect coastal rail infrastructure

Please share any learning points that you are aware of being obtained through using reefs and/or mangroves to protect coastal rail infrastructure

Question 5

Please select the top 3 barriers that you believe limit the use of nature-based solutions as climate change adaptation measures for rail infrastructure

- ☐ Safety concerns
- ☐ Time it may take for natural solutions to grow
- ☐ Lack of cost benefit analysis
- ☐ Limited land availability
- ☐ Climate change uncertainties
- ☐ Third party stakeholder issues
- ☐ Lack of awareness on nature based solutions
- ☐ Lack of examples of nature based solutions used in rail
- ☐ Cost
- ☐ Maintenance requirements

- [ ] Rail industry resistance to change
- [ ] Lack of regulations and/or standards mandating their use
- [ ] Other

If you selected Other, please specify:

Question 6

Please select the top 3 measures that you believe would enable the widespread uptake of nature-based solutions as climate change adaptation measures for rail infrastructure.

Please select exactly 3 answer(s).

- [ ] Legislation mandating use
- [ ] Rail Policy and Standards mandating use
- [ ] Client specification
- [ ] Education and training
- [ ] Partnerships with neighbouring land owners
- [ ] Cost Benefit Analyses to allow the comparisons of climate change adaptation options
- [ ] Provision of funding and incentives
- [ ] Other

If you selected Other, please specify:

Question 7

Please select the top 3 mechanisms that you believe would support the implementation of nature-based solutions as climate change adaptation measures for rail.

Please select exactly 3 answer(s).

- [ ] Standards and guidance

- [ ] Cross sector collaboration (e.g. with highways, utilities)
- [ ] Cross regional and/or international collaboration
- [ ] Test and demonstration sites
- [ ] Education and training
- [ ] Access to or the involvement of subject matter experts
- [ ] Further research
- [ ] Funding and incentives
- [ ] Shared case studies
- [ ] Webinar sessions with presenters sharing examples
- [ ] Catalogue of nature-based solution options
- [ ] Other

If you selected Other, please specify:

Participant Data

Job title (please write in full, no acronyms)

Location (country)

Length of rail industry experience

- ○ < 1 year
- ○ 1-4 years
- ○ 5-9 years
- ○ 10 - 19 years
- ○ 20 + years

Nature of your organisation (e.g. Infrastructure Owner, Designer, Constructor, Maintainer, Standards Board, Consultancy, Supply Chain)

Which of the rail infrastructure lifecycle stages does your role support? Please select all that apply.

- [ ] Planning
- [ ] Design
- [ ] Construction
- [ ] Operation
- [ ] Maintenance/Renewal/Enhancement
- [ ] Decommissioning
- [ ] I don't know

Final page

Thank you for taking the time to complete this survey, your participation is very much appreciated.

Appendix C Supplementary text S1 (Chapter 5)

Case Study Focus Group & Interview Question Set

Victoria Square, Adelaide	**Brumber Hill Culvert, UK**
What is or was your involvement with the green track?	What is or was your involvement with the vegetated culvert?
What are your general thoughts on the green track?	What are your general thoughts on the vegetated culvert?
Have you encountered problems in using green track?	Have you encountered problems in using vegetated culvert?
What has worked well using green track, have there been benefits?	What has worked well using vegetated culvert, have there been benefits?
Would you be keen to see green track used elsewhere?	Would you be keen to see vegetated culvert used elsewhere?
Why/why not?	Why/why not?
Confirm the lifecycle stages participants are involved at.	Confirm the lifecycle stages participants are involved at.
Is there interaction with stakeholders between stages?	Is there interaction with stakeholders between stages?
What about for a new track or upgrade project?	What about for a new track or upgrade project?
Where and how is information communicated, are records kept?	Where and how is information communicated, are records kept?
Framework involves completion of a CCRA – do you complete these?	Framework involves completion of a CCRA – do you complete these?
Have you seen or been involved for one for AMO (or elsewhere)?	Have you seen or been involved for one for BHC (or elsewhere)?
A key step is to identify climate change adaptation options, are you familiar with any measures?	A key step is to identify climate change adaptation options, are you familiar with any measures?
What examples have you been involved with? Grey/green/hybrid?	What examples have you been involved with? Grey/green/hybrid?
The recommendation here is for CCRA to take part at early design stage – thoughts on this?	The recommendation here is for CCRA to take part at early design stage – thoughts on this?
Operation feedback loop to design – how much re-design happens versus replace with existing material set up without consideration of other options?	Operation feedback loop to design – how much re-design happens versus replace with existing material set up without consideration of other options?
Key step to get NbS into the design is in blue (i) do the CCRA (ii) know that there's a tried and tested option available suitable for rail – does this look to be the most likely route?	Key step to get NbS into the design is in blue (i) do the CCRA (ii) know that there's a tried and tested option available suitable for rail – does this look to be the most likely route?
Who is likely to be involved in these steps?	Who is likely to be involved in these steps?
Are co-development opportunities likely (at AMO)?	Are co-development opportunities likely (at BHC)?
Feedback between operation and design?	Feedback between operation and design?
Have extreme weather events impacted operations?	Have extreme weather events impacted operations?
Has this led to reconsideration of design?	Has this led to reconsideration of design?
Has there been noted difference in flood/drainage between non/green track sections of track?	Has there been noted difference in flood/drainage between non/vegetated culvert sections of track?
Thoughts on current grass species used e.g. during drought conditions – what would be the likely steps if this species needed to be changed due to changing climate (would or could it follow the left-hand wheel)?	Thoughts on current vegetation species used e.g. during drought conditions – what would be the likely steps if this species needed to be changed due to changing climate (would or could it follow the left-hand wheel)?

Appendix D Supplementary text S2 (Chapter 5)

University of Glasgow

Nature-based solutions for rail climate change adaptation

Case Study: Green track at Victoria Square, Adelaide

Green track was installed to sections of the Adelaide Metro tram network to integrate the tramline with the surrounding parkland in Victoria Square.

Traditionally, the space between tram tracks is filled with concrete, ballast or asphalt. Kikuyu grass turf was planted on approximately 180 metres of the track in Victoria Square.

Through an interface agreement between the rail infrastructure owner, tram operator and grass maintainer, the grass sections have remained well established since being planted in 2007, without causing safety or operational issues to rail infrastructure or tram services.

Credit: Yuen Man Cheung / Alamy Stock Photo

Key: Green track sections

Location SA Viewer by the Government of South Australia under CC BY

Green track is a 'nature-based solution' that uses natural interventions instead of or alongside conventional engineered measures to provide sustainable options that benefit people and the environment.

The benefits of green track include:

- Improved water retention and drainage regulation to help reduce flooding
- Cooling effects caused by evaporation from vegetation
- Improved air and water quality by filtering dust out of the air and pollutants out of stormwater
- Reduced rail noise and glare from concrete
- Enhanced natural habitat and increased biodiversity

For further information contact: l.blackwood.2@research.gla.ac.uk

Appendix E Supplementary text S3 (Chapter 5)

University of Glasgow

Nature-based solutions for rail climate change adaptation
Case Study: Vegetated culvert headwall on the Transpennine Route Upgrade rail programme

A vegetated culvert headwall was installed at Brumber Hill in Yorkshire, UK, as part of the Transpennine Route Upgrade rail programme across northern England.

Traditionally, headwall structures would be constructed from pre-cast concrete or gabion baskets. In this instance 'Flex MSE' geotextile bags were used to build a modular retaining wall which was then planted with vegetation, combining an engineered approach with a 'nature-based solution'.

This hybrid bioengineered approach provides a strengthened headwall structure and increased drainage capacity to protect the culvert and upstream rail infrastructure from, and allow it to accommodate, the increase in precipitation and flood events that are predicted with climate change.

Culvert headwall at installation, June 2021

Credit: York Consortium Drainage Board, 2021

Vegetation established on culvert headwall, 2023

Credit: Scott Parnell Ltd. (2022)

Incorporating a nature-based solution, the structure also delivers the following benefits:

- Improved water retention and drainage regulation to help reduce flooding
- Improved air and water quality by filtering dust out of the air and pollutants out of stormwater
- Enhanced natural habitat and increased biodiversity
- Controls soil erosion and sedimentation.

For further information contact: l.blackwood.2@research.gla.ac.uk

Appendix F Nature-based solutions for rail climate change adaptation: A framework for incorporation

Nature-based solutions for rail climate change adaptation: A framework for incorporation

Climate change is increasing the frequency and severity of extreme weather events that impact railway services and infrastructure. Climate change adaptation is therefore required to increase rail infrastructure resilience to withstand the projected conditions and ensure the ongoing provision of safe, cost-effective services.

The adaptation measures used on rail infrastructure have typically involved 'grey' engineered solutions such as seawalls and increasing the size of drainage culverts. 'Nature-based solutions' (NbS) have more recently been suggested as an alternative or complementary solution to grey options. NbS comprise of a range of approaches that manage and use ecosystems to benefit society and nature. As an example, the vegetation planted on green roofs reduces stormwater runoff and decreasing the urban heat island effect. Two rail-specific examples of NbS providing climate change adaptation benefits are shown below.

Vegetated headwall culvert, Brumber Hill, UK
(Photo credit: Scott Parnell Ltd., 2022)

The strengthened culvert headwall incorporates vegetation to protect the culvert and upstream rail infrastructure from the increase in rainfall and flood events predicted with climate change.

Green track at Victoria Square, Adelaide, Australia

Grassed track improves water retention and drainage to help avoid flooding and provides a local temperature cooling effect.

Incorporating a nature-based solutions can deliver additional benefits including:

- Improved air and water quality by filtering dust out of the air and pollutants out of stormwater
- Enhanced natural habitat and increased biodiversity
- Low carbon options which can contribute to industry carbon reduction targets
- Improved aesthetics and provision of noise/light screening which can aid wellbeing

With the rail industry's need to adapt infrastructure to withstand the impacts of climate change growing rapidly, and recognising the many advantages that can be gained by using natural solutions, a framework has been prepared to aid the integration of NbS into rail infrastructure (see next page).

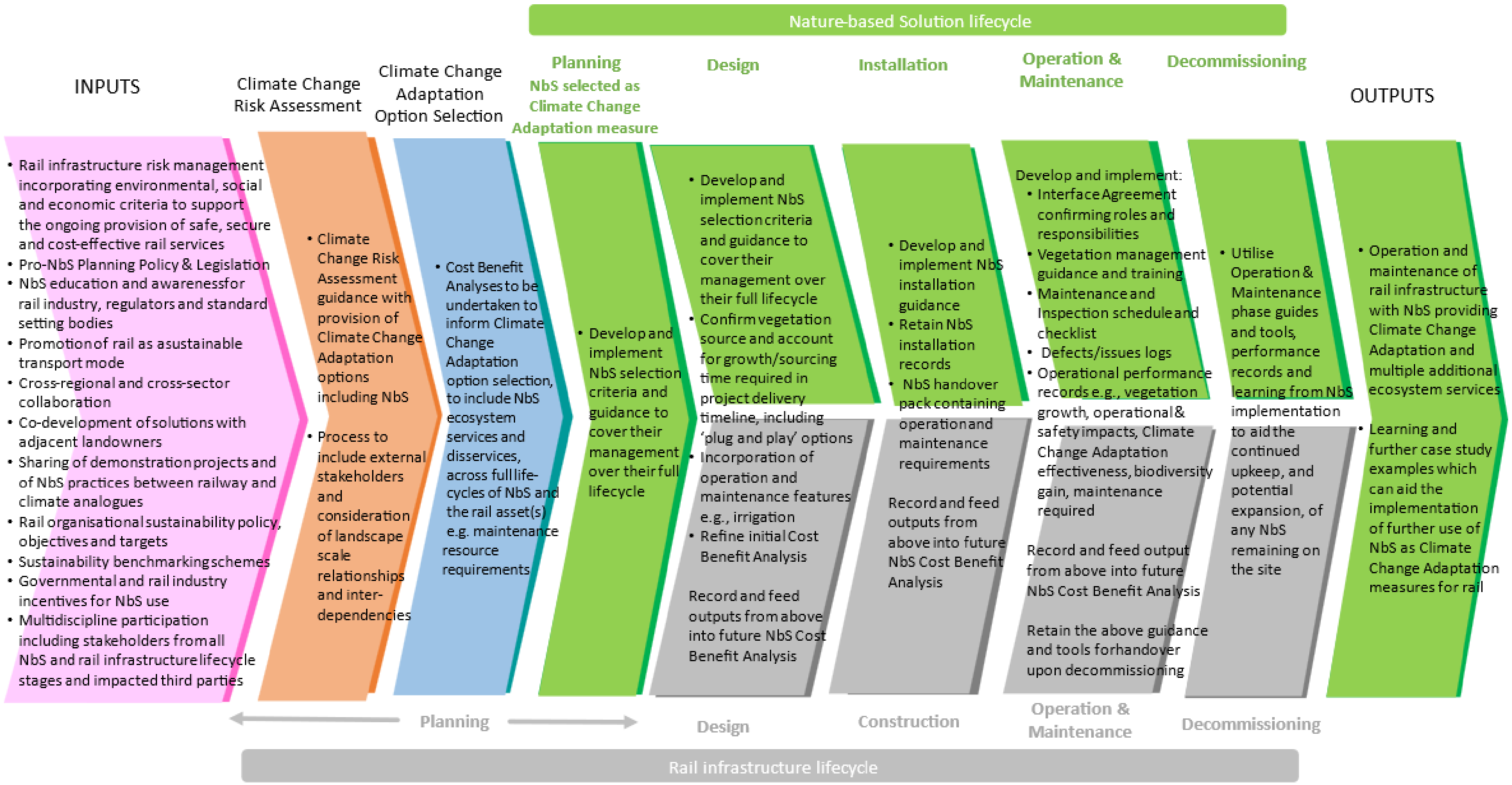
The framework has been developed in consultation with rail industry professionals and includes practical recommendations to aid the roll out of NbS, taking account of the barriers that may be faced in attempting to implement NbS in the rail sector.

For further information contact: l.blackwood.2@research.gla.ac.uk

University of Glasgow

Nature-based solutions for rail climate change adaptation:

A framework for incorporation



For further information contact: l.blackwood.2@research.gla.ac.uk

Appendix G Relevance of the framework to implement NbS as CCA for rail to the IUCN Global Standard for NbS and its underpinning principles

Reference	NbS Principle (Cohen-Shacham et al., 2016), Global Standard Criterion or Indicator (IUCN, 2020)	**The relevance and alignment (or otherwise) of the framework to implement NbS as CCA for rail (**Figure 5-4**) with each NbS Principle/Criterion/Indicator**
Criterion 1	**NbS effectively address societal challenges**	The framework has been developed to support the implementation of NbS on rail infrastructure in response to a significant, global societal challenge: climate change. NbS are being increasingly viewed as a sustainable approach to address negative climate change impacts, both in terms of CCA and mitigation. A key framework input is the ***Promotion of rail as a sustainable transport mode***, and the strategic imperative of the framework is to enable the ongoing provision of safe, reliable and cost-effective rail services, thereby supporting societal challenges around climate change, human health, and economic and social development. Rail infrastructure owners are generally Statutory Undertakers i.e., bodies that have been given statutory powers to discharge functions that are of a public nature, allowing them to carry out certain works without obtaining normal permissions (Designing Buildings, 2024). Combined with the (largely) private ownership of rail infrastructure, this means that taking actions on their own land to ensure safe rail operations may take rail infrastructure owner priority over public preferences. Therefore, the CCA responses selected by the rail industry may not always be viewed as 'fair and equitable' by the wider community. Rail infrastructure projects do generally involve public consultation via transparent processes, however (see e.g., Public Transport Projects Alliance, 2024), and the framework includes the ***Co-***
Principle 4	**NbS produce societal benefits in a fair and equitable way in a manner that promotes transparency and broad participation**	

Reference	NbS Principle (Cohen-Shacham et al., 2016), Global Standard Criterion or Indicator (IUCN, 2020)	**The relevance and alignment (or otherwise) of the framework to implement NbS as CCA for rail (**Figure 5-4**) with each NbS Principle/Criterion/Indicator**
		development of solutions with adjacent landowners as a process input to encourage stakeholder participation in the rail infrastructure and NbS intervention lifecycles.
Indicator 1.1	**The most pressing societal challenge(s) for rights-holders and beneficiaries are prioritised**	By contributing to the ongoing provision of public transport (a green, carbon mitigating travel mode), connecting people to jobs, education, healthcare, leisure and enabling the provision of essential food and medical supplies, this research supports societal challenges around climate change, human health, and economic and social development. Transparency of risk-based decision making can be provided through the sharing of and public accessibility to records of CCRA and of the CBA undertaken to identify the 'most pressing' societal challenges, and the selection of the most reasonably practicable solution. The CBA process will allow the quantification, recording and sharing of the societal benefits (and disservices) of the NbS implementation. Framework steps (***Inputs*** and ***Climate Change Risk Assessment***) incorporate the co-development of solutions with landowners and multi-stakeholder participation in CCRA, which will enable inclusive consultation. The tool therefore promotes wider community consultation and the potential to collaboratively develop landscape scale solutions which may help to address a wider range of societal challenges, on a wider geographic scale.

Reference	NbS Principle (Cohen-Shacham et al., 2016), Global Standard Criterion or Indicator (IUCN, 2020)	The relevance and alignment (or otherwise) of the framework to implement NbS as CCA for rail (Figure 5-4) with each NbS Principle/Criterion/Indicator
Indicator 1.2	**The societal challenge(s) addressed are clearly understood and documented**	The CCRA and CBA processes integral to the framework can be used to identify and quantify (i.e., understand), and provide a format in which to document, the type and extent of the societal challenges that the proposed rail infrastructure and CCA (including NbS) intervention(s) are intended to address. The CBA should document all ecosystem services and disservices associated with the NbS implementation. The overriding priority for rail infrastructure owners will be the ongoing provision of safe, reliable rail services; this may be to the detriment of rail industry (and wider community at the landscape scale) uptake of NbS, and the subsequent provision of wider ecosystem services to address societal challenges additional to climate change. The recording and sharing of CCRA and CBA outputs during the NbS and rail infrastructure lifecycle Design, Construct/Installation, and Operation and Maintenance stages, and lessons learned will enable the tracking of NbS implementation status and performance levels. This activity can help to ensure accountability for the ongoing management of the NbS. Roles and responsibilities should be clearly documented in the Operation & Maintenance phase Interface Agreement, and the documented record keeping format can provide a vehicle to provide transparency.

Reference	NbS Principle (Cohen-Shacham et al., 2016), Global Standard Criterion or Indicator (IUCN, 2020)	**The relevance and alignment (or otherwise) of the framework to implement NbS as CCA for rail (**Figure 5-4**) with each NbS Principle/Criterion/Indicator**
Indicator 1.3	**Human well-being outcomes arising from the NbS are identified, benchmarked and periodically assessed**	The full extent of human well-being outcomes arising from NbS implementation can be identified during the CBA conducted as part of the CCA option selection process. These outcomes should be quantified where practicable to allow an appreciation of the full range of ecosystem service benefits (and disservices), and enable a holistic comparison of all CCA options being considered. The substantive, and rail industry priority towards beneficial human wellbeing outcomes, will be the use of NbS to deliver CCA to enable the fulfillment of social and economic connection through the ongoing provision of safe and reliable public transport. Indirectly, NbS can provide aesthetical enjoyment to the travelling public and communities adjoining railway land, which can positively impact mental health well-being. The framework input of ***Promoting rail as a sustainable transport*** mode can support the concept of 'active mobility', which connects public transport with active travel modes (i.e., walking and cycling) (Arup, 2024). As well as directly benefiting physical wellbeing, encouraging active mobility can help reduce pollutant emitting private car journeys which, in addition to the climate change mitigating advantages gained, will improve local air quality, which will in turn provide health benefits. The ongoing monitoring of NbS performance during the framework's Operation & Maintenance

Reference	NbS Principle (Cohen-Shacham et al., 2016), Global Standard Criterion or Indicator (IUCN, 2020)	The relevance and alignment (or otherwise) of the framework to implement NbS as CCA for rail (Figure 5-4) with each NbS Principle/Criterion/Indicator
		phase will provide the opportunity to periodically assess the extent of actual human well-being outcomes against those benchmarked during the CBA process, and prompt the need for improvement where required. Roles and responsibilities for these activities should be captured in the ***Interface Agreement***.
Criterion 2	**Design of NbS is informed by scale**	The framework is applicable to the full scope of rail infrastructure - including the geographic footprint of the rail infrastructure and NbS, and their respective lifespan timescales.
Indicator 2.1	**The design of the NbS recognises and responds to interactions between the economy, society and ecosystems**	The framework sees NbS design being integrated to the rail infrastructure lifecycle management process and its overarching risk management ethos which incorporates environmental, social and economic considerations. The CCRA process can be used to identify economic, societal and ecosystem interactions and the risk that they may present to rail infrastructure, and to NbS interventions, including the risk presented by the implementation of CCA responses - whether they be NbS, grey or hybrid measures. Environmental Impact Assessments (EIA) and/or other socio-economic and environmental assessments undertaken during rail infrastructure planning and design stages (which identify interactions between the economy, society and ecosystems) can be used to

Reference	NbS Principle (Cohen-Shacham et al., 2016), Global Standard Criterion or Indicator (IUCN, 2020)	The relevance and alignment (or otherwise) of the framework to implement NbS as CCA for rail (Figure 5-4) with each NbS Principle/Criterion/Indicator
		inform the CCRA, and subsequently the CCA option selection process and CBA. The framework requires the consideration of such interactions over the full lifecycle of the rail infrastructure.
Principle 2	**NbS can be implemented alone or in an integrated manner with other solutions to societal challenges (e.g., technological and engineering solutions)**	The final version of the framework (Figure 5-4) fully integrates NbS design into the rail infrastructure lifecycle management process. Process inputs include ***Cross-sector collaboration*** with other industries (e.g., electricity and telecommunication utilities); this includes the provision for ***Interface Agreements*** during the Operation and Maintenance stage which will help to ensure accountability for cross-discipline and cross-sector management of NbS where required. The promotion of grey-green ('hybrid') CCA measures in this research i.e., integrating natural solutions with engineered interventions, also supports this indicator.
Indicator 2.2	**The design of the NbS is integrated with other complementary interventions and seeks synergies across sectors**	
Indicator 2.3	**The design of the NbS incorporates risk**	The framework and NbS design process are embedded within the overarching risk management of rail infrastructure; to ensure the ongoing provision of safe, secure and

Reference	NbS Principle (Cohen-Shacham et al., 2016), Global Standard Criterion or Indicator (IUCN, 2020)	The relevance and alignment (or otherwise) of the framework to implement NbS as CCA for rail (Figure 5-4) with each NbS Principle/Criterion/Indicator
	identification and risk management beyond the intervention site	cost-effective services, the decision-making process to apply NbS for CCA must inherently consider the rail infrastructure beyond the immediate location of the NbS intervention placement. The framework Inputs stage includes the ***Co-development of solutions with adjacent landowners*** therefore encouraging the consideration of stakeholders and impacts at the wider landscape scale. EIA and/or other socio-economic and environmental assessments undertaken during the rail infrastructure planning and design stages will consider the stakeholders, interests and ecosystems outside the immediate intervention area. Outputs from such studies should be utilised during CCRA and CBA processes to identify and quantity climate and other environmental, social and economic risks and opportunities within and beyond the intervention site, and prompt the incorporation of their management into the NbS design.
Principle 6	**NbS are applied at a landscape scale.**	
Principle 1	**NbS embrace nature conservation norms (and principles)**	The framework Inputs include ***Rail organisational sustainability policy, objectives and targets***; industry-wide these are increasingly including biodiversity targets e.g., no net loss and net positive biodiversity. Combined with the use of ***Sustainability***

Reference	NbS Principle (Cohen-Shacham et al., 2016), Global Standard Criterion or Indicator (IUCN, 2020)	**The relevance and alignment (or otherwise) of the framework to implement NbS as CCA for rail (**Figure 5-4**) with each NbS Principle/Criterion/Indicator**
Criterion 3	**NbS result in a net gain to biodiversity and ecosystem integrity**	***benchmarking schemes***, which also drive nature conservation and biodiversity gain through infrastructure design and construction, rail industry efforts towards these goals will push the industry to examine opportunities to conserve, restore and install native vegetation on and/or close to their infrastructure. This will create an incentive for railways to utilise NbS as CCA measures by enabling rail to work towards industry biodiversity goals whilst simultaneously providing CCA responses. The CBA process can be used to quantify and set targets for ecosystem conservation efforts, and the contribution to biodiversity and ecosystem integrity provided by the NbS intervention(s) deployed. Progress can then be tracked during the Operation & Maintenance period, with NbS performance being monitored in accordance with the documented ***Interface Agreement*** roles and responsibilities to maintain accountability for achievement of NbS, biodiversity and wider sustainability targets.
Indicator 3.1	**The NbS actions directly respond to evidence-based assessment of the current state of the**	Rail infrastructure Planning and Design stage EIAs and associated surveys can be used to measure and record ecological baselines, before the installation and/or restoration and conservation of NbS. The ongoing performance of NbS can then be recorded through the lifecycle of the NbS intervention/rail infrastructure as per the Operation & Maintenance phase activities.

Reference	NbS Principle (Cohen-Shacham et al., 2016), Global Standard Criterion or Indicator (IUCN, 2020)	The relevance and alignment (or otherwise) of the framework to implement NbS as CCA for rail (Figure 5-4) with each NbS Principle/Criterion/Indicator
	ecosystem and prevailing drivers of degradation and loss	Whilst the installation, conservation and/or restoration of NbS should enhance biodiversity in the rail environment, due to rail operational safety requirements (see Chapter 3.1) the removal (i.e., loss) of NbS may be essential in some instances; in such cases, the rationale for decisions to decommission NbS should be recorded to inform the planning of future NbS interventions. Also, because grey engineered CCA interventions may be required on and/or adjacent to rail infrastructure alongside or combined with NbS interventions to provide larger scale, more robust CCA measures than can be delivered by NbS alone, the land take required may mean that the removal of vegetation is unavoidable, and that biodiversity gains can therefore not always be guaranteed.
Indicator 3.2	**Clear and measurable biodiversity conservation outcomes are identified, benchmarked and periodically assessed**	As per the above response for Indicator 3.1, baseline ecology surveys can be used to inform the setting of biodiversity conservation targets. These should be aligned with the framework inputs of ***Rail organisational sustainability policy, objectives and targets***, and the implementation of ***Sustainability benchmarking schemes***. The ongoing performance of NbS and their contribution towards biodiversity targets can then be monitored and evaluated through the lifecycle of the NbS intervention/rail infrastructure, as per the Operation & Maintenance phase activities, with roles and responsibilities for these activities confirmed in ***Interface Agreements***.

Reference	NbS Principle (Cohen-Shacham et al., 2016), Global Standard Criterion or Indicator (IUCN, 2020)	The relevance and alignment (or otherwise) of the framework to implement NbS as CCA for rail (Figure 5-4) with each NbS Principle/Criterion/Indicator
Indicator 3.3	**Monitoring includes periodic assessments of unintended adverse consequences on nature arising from the NbS**	The CBA process includes the consideration of both the ecosystem benefits and disservices of NbS interventions. These will be monitored and evaluated through the lifecycle of the NbS intervention and rail infrastructure, as per the Operation & Maintenance phase activities, with frequent inspection and maintenance regimes providing the opportunity to identify any unintended adverse consequences. Recognising that the overarching concern for rail infrastructure owners shall always be the ongoing provision of safe, secure and cost-effective rail services, there may be occasions where unintended adverse consequences on nature arising from NbS may have to be factored in order to maintain safe railway operations. As an example, it has been suggested (but not confirmed) that a mammal may have burrowed a hole into the vegetated culvert headwall examined in the BHC case study (refer Chapter 5.5.4). Should this be the case, and the hole worsens and compromises the structural integrity of the headwall, the vegetated section may have to be replaced with a concrete (or similar) structure, requiring the removal of an established habitat and disturbance to the species using it.
Indicator 3.4	**Opportunities to enhance ecosystem**	The incorporation of NbS into rail infrastructure instead of and/or alongside traditional grey CCA measures is intended to enhance ecosystem integrity and connectivity.

Reference	NbS Principle (Cohen-Shacham et al., 2016), Global Standard Criterion or Indicator (IUCN, 2020)	**The relevance and alignment (or otherwise) of the framework to implement NbS as CCA for rail (**Figure 5-4**) with each NbS Principle/Criterion/Indicator**
	integrity and connectivity are identified and incorporated into the NbS strategy	Fenced railway corridors can provide secure environments that allow the enhancement of ecosystem integrity however fences may present physical barriers to ecosystem connectivity (see Chapter 3.3).
Criterion 4	**NbS are economically viable**	The undertaking of CBA is fundamental to the framework, the process is to be performed to include ecosystem dis/services including financial cost, considering the full lifecycles of the NbS intervention and the rail infrastructure for which CCA is being developed. Prompts during the Design, Installation, Operation & Maintenance phases require assessment against the initial CBA, and the sharing of outputs to inform CBA for potential future CBA. Monitoring and evaluation of the costs involved, including forecast versus actual, will allow an assessment of the economic viability of NbS, and a comparison against the whole lifecycle costs of traditional grey CCA interventions. ***Government and rail industry incentives for NbS use*** is included as a framework input. Whilst the economic viability of NbS implementation in rail is yet to be confirmed, by providing financial motivation to use the concepts this may quell reluctance to trial NbS concepts due to cost concerns and/or uncertainties.

Reference	NbS Principle (Cohen-Shacham et al., 2016), Global Standard Criterion or Indicator (IUCN, 2020)	The relevance and alignment (or otherwise) of the framework to implement NbS as CCA for rail (Figure 5-4) with each NbS Principle/Criterion/Indicator
Indicator 4.1	**The direct and indirect benefits and costs associated with the NbS, who pays and who benefits, are identified and documented**	Direct and indirect costs and benefits, and their respective beneficiaries and cost bearers can be identified and documented through the CBA process. Learning can be gained by comparing costs forecast during the CCA option selection process with actual expenditure outlay during the Operation & Maintenance of the NbS intervention. Rail infrastructure owners will be accountable for providing safe and structurally sound infrastructure on which to operate rail services and will bear costs for this, for example in the form of delay compensation payments made to train operators (Network Rail, 2024d). Beneficiaries of NbS ecosystem services will include the travelling public who retain access to safe, reliable rail services and may enjoy aesthetic benefits of passing through scenic areas containing NbS, as may local stakeholders who live in proximity of the NbS intervention.

Reference	NbS Principle (Cohen-Shacham et al., 2016), Global Standard Criterion or Indicator (IUCN, 2020)	The relevance and alignment (or otherwise) of the framework to implement NbS as CCA for rail (Figure 5-4) with each NbS Principle/Criterion/Indicator
Indicator 4.2	**A cost-effectiveness study is provided to support the choice of NbS including the likely impact of any relevant regulations and subsidies**	As per Indicator 4.1, the undertaking of CBA will enable consideration of economic costs of NbS interventions over their full lifecycle, for example routine maintenance costs. Through the application of the framework, CBA will be conducted within the scope of the rail industry's overarching environmental, social and economic risk management and associated legal compliance framework, which will allow for regulatory compliance costs to be identified and accounted for. ***Governmental and rail industry incentives for NbS use***, which may be in the form of subsidies, is included as a framework input; where applicable these should also be reflected in the CBA.
Indicator 4.3	**The effectiveness of the NbS design is justified against available alternative solutions, taking into account any associated externalities**	The CBA process is fundamental to the CCA option selection process. The CBA will enable the comparison of multiple solutions including NbS, traditional grey options, and hybrid grey-green CCA measures. The priority in any decision-making undertaken for railway infrastructure is safety, and the implementation of NbS may be discounted or decommissioned on safety grounds, even if all other CBA considerations present NbS as a favourable CCA option.

Reference	NbS Principle (Cohen-Shacham et al., 2016), Global Standard Criterion or Indicator (IUCN, 2020)	**The relevance and alignment (or otherwise) of the framework to implement NbS as CCA for rail (**Figure 5-4**) with each NbS Principle/Criterion/Indicator**
Indicator 4.4	**NbS design considers a portfolio of resourcing options such as market-based, public sector, voluntary commitments and actions to support regulatory compliance**	Depending on the railway land or infrastructure owner (e.g., whether it is privately or state owned), different funding arrangements may be available to finance the installation of NbS. Private infrastructure owners may not be willing to design (i.e., fund the provision of) NbS beyond the extent of their ownership remit, however partnerships may be developed to implement landscape-scale interventions which straddle land adjacent to the railway. Such interventions would be more accessible to and provide more direct ecosystem service benefits to the local community, and if not voluntarily delivered by the rail infrastructure owner, they may attract public sector funding and/or joint funding with wildlife and nature conservation organisations. ***Governmental and rail industry incentives for NbS use*** is included as a framework input; where applicable these should also be reflected in the CBA.
Criterion 5	**NbS are based on inclusive, transparent and empowering governance processes**	As per the Criterion 1 and Principle 4 responses above, rail infrastructure owners are generally Statutory Undertakers which allows them to carry out certain works without obtaining normal permissions and/or perform public consultation on actions they take to maintain safe railway operations; this may include installing CCA responses such as NbS. Therefore, the processes used by the rail industry to implement NbS may not always be viewed as ‘inclusive’ and/or ‘empowering’ by the wider community.

Reference	NbS Principle (Cohen-Shacham et al., 2016), Global Standard Criterion or Indicator (IUCN, 2020)	The relevance and alignment (or otherwise) of the framework to implement NbS as CCA for rail (Figure 5-4) with each NbS Principle/Criterion/Indicator
		Rail infrastructure projects do generally involve public consultation via transparent processes, however (see e.g., Public Transport Projects Alliance (2024)), and the framework includes the ***Co-development of solutions with adjacent landowners*** as a process input to encourage stakeholder participation in the rail infrastructure and NbS intervention lifecycles.
Indicator 5.1	**A defined and fully agreed upon feedback and grievance resolution mechanism is available to all stakeholders before an NbS intervention is initiated**	Within the rail industry, the multi-discipline and multi-lifecycle stage participation of internal stakeholders during the CCRA process allows for dialogue with and feedback from a variety of rail consultees prior to the initiation of an NbS intervention. The step of recording and providing feedback from the NbS Design, Installation and Operation & Maintenance framework stages to inform future CBA will allow for any negative feedback and/or grievances to be raised and flagged during the CCA selection process before initiating new NbS interventions. The Operation & Maintenance phase specifically includes ***Defects/issues logs*** which can be used to record any such feedback. Roles and responsibilities, including reporting channels and accountabilities for responding to grievances, should be confirmed in the Operation & Maintenance ***Interface Agreement*** arrangements. As a safety critical industry, railways require all employees to immediately report any safety concern which has the potential to harm a person and/or

Reference	NbS Principle (Cohen-Shacham et al., 2016), Global Standard Criterion or Indicator (IUCN, 2020)	The relevance and alignment (or otherwise) of the framework to implement NbS as CCA for rail (Figure 5-4) with each NbS Principle/Criterion/Indicator
		rail infrastructure (see for example Network Rail (2024e). Any safety concerns that have been raised regarding NbS on or near railways should be taken into account when considering the implementation of NbS on rail infrastructure, such concerns should be considered as ecosystem disservices and quantified during the CBA and reflected in the CCA selection process. For parties external to the rail industry, public feedback and grievances can be formally raised during the consultation phase undertaken during the planning of rail infrastructure projects. Many rail infrastructure owners provide multi-media communication channels (see e.g., Network Rail (2024c)) which can be used to submit feedback, they may also have established complaint handling procedures which outline arrangements for and commitments to dealing with grievances (e.g., Network Rail (2024b)) which may include specific arrangements for vegetation related concerns (e.g., (Network Rail, 2024f).
Indicator 5.2	**Participation is based on mutual respect and equality, regardless of gender, age or social status, and upholds the**	Refer to response provided for Criterion 5.

Reference	NbS Principle (Cohen-Shacham et al., 2016), Global Standard Criterion or Indicator (IUCN, 2020)	The relevance and alignment (or otherwise) of the framework to implement NbS as CCA for rail (Figure 5-4) with each NbS Principle/Criterion/Indicator
	right of Indigenous Peoples to Free, Prior and Informed Consent (FPIC)	
Indicator 5.3	**Stakeholders who are directly and indirectly affected by the NbS have been identified and involved in all processes of the NbS intervention**	As per response provided for Criterion 5, all affected stakeholders may not necessarily be consulted on or involved with the design of an NbS intervention or rail infrastructure or land. Stakeholder mapping may be conducted during rail infrastructure projects (see for example Melbourne Metro Rail Authority (2017)). Affected stakeholders who will be directly or indirectly impacted by an NbS intervention should be considered during the CCRA, and the potential ecosystem service benefits and disservices they receive from NbS should be considered and quantified during the CBA process to inform the CCA selection.
Indicator 5.4	**Decision-making processes document and respond to the rights and interests of**	Outputs from CCRA and CBA, including their consideration of the points provided above in reference to Criterion 5 and Indicators 5.1 and 5.3, should be recorded and made publicly available to provide accessibility to and full transparency of decision making relating to NbS implementation and/or other CCA measures selected.

Reference	NbS Principle (Cohen-Shacham et al., 2016), Global Standard Criterion or Indicator (IUCN, 2020)	The relevance and alignment (or otherwise) of the framework to implement NbS as CCA for rail (Figure 5-4) with each NbS Principle/Criterion/Indicator
	all participating and affected stakeholders	
Indicator 5.5	**Where the scale of the NbS extends beyond jurisdictional boundaries, mechanisms are established to enable joint decision making of the stakeholders in the affected jurisdictions**	The ***Co-development of NbS with adjacent landowners*** is included as a key framework input. Consultation with wider stakeholders will generally be undertaken during infrastructure project planning and design consultation stages. Following the co-development of a transboundary NbS intervention, arrangements for its ongoing operation and maintenance, including roles and responsibilities, should be confirmed in an ***Interface Agreement***.
Criterion 6	**NbS equitably balance trade-offs between achievement of their primary goal(s) and the continued provision of multiple benefits**	Due to the safety criticality of rail infrastructure, the overriding priority shall always be safety and there should be no 'trade-offs' in this regard.

Reference	NbS Principle (Cohen-Shacham et al., 2016), Global Standard Criterion or Indicator (IUCN, 2020)	The relevance and alignment (or otherwise) of the framework to implement NbS as CCA for rail (Figure 5-4) with each NbS Principle/Criterion/Indicator
Principle 7	**NbS recognize and address the trade-offs between the production of a few immediate economic benefits for development, and future options for the production of the full range of ecosystem services**	
Indicator 6.1	**The potential costs and benefits of associated trade-offs of the NbS intervention are explicitly acknowledged and inform safeguards**	The costs and benefits of NbS implementation will be identified and quantified during CBA and then formally monitored during the remainder of the intervention/rail infrastructure's lifecycle. At no point should 'trade offs' be made that compromise the integrity of rail infrastructure or the safe and secure operation of rail services (Refer Chapter 3.3.1).

Reference	NbS Principle (Cohen-Shacham et al., 2016), Global Standard Criterion or Indicator (IUCN, 2020)	The relevance and alignment (or otherwise) of the framework to implement NbS as CCA for rail (Figure 5-4) with each NbS Principle/Criterion/Indicator
	and any appropriate corrective actions	
Principle 3	**NbS are determined by site-specific natural and cultural contexts that include traditional, local and scientific knowledge**	Refer to the responses provided above for Criterion 5 and its associated indicators.
Indicator 6.2	**The rights, usage of and access to land and resources, along with the responsibilities of different stakeholders, are acknowledged and respected**	
Indicator 6.3	**The established safeguards are**	Refer to the response provided above for Indicator 6.1, no trade-offs should be made which could compromise the safe operation of rail infrastructure. The regular inspection

Reference	NbS Principle (Cohen-Shacham et al., 2016), Global Standard Criterion or Indicator (IUCN, 2020)	The relevance and alignment (or otherwise) of the framework to implement NbS as CCA for rail (Figure 5-4) with each NbS Principle/Criterion/Indicator
	periodically reviewed to ensure that mutually-agreed trade-off limits are respected and do not destabilise the entire NbS	and monitoring of NbS undertaken (as per the ***Inspection and Maintenance Schedule*** during its Operation & Maintenance phase) should be used to ensure the implementation of NbS does not destabilise the rail infrastructure, as opposed to the stability of the NbS being a priority concern. As part of the rigorous risk management of rail infrastructure which overarches the NbS framework, there will be regular evaluation and assessment of effectiveness of risk control and mitigation safeguard measures. As discussed above, this may necessitate the decommissioning of NbS on rail safety and/or operational grounds.
Criterion 7	**NbS are managed adaptively, based on evidence**	The framework provides for the ongoing monitoring of NbS performance with multiple feedback loops to provide data and learned experience from its implementation. The aim of this data is to aid the further roll out of NbS elsewhere, including the need for changes in NbS design and implementation, for example adaptation in NbS management practices and species selection if required.
Principle 5	**NbS maintain biological and cultural diversity and the ability of ecosystems to evolve over time**	

Reference	NbS Principle (Cohen-Shacham et al., 2016), Global Standard Criterion or Indicator (IUCN, 2020)	The relevance and alignment (or otherwise) of the framework to implement NbS as CCA for rail (Figure 5-4) with each NbS Principle/Criterion/Indicator
Indicator 7.1	**A NbS strategy is established and used as a basis for regular monitoring and evaluation of the intervention**	The strategy for NbS management has been integrated with the existing, robust, inspection and maintenance regime undertaken as part of the risk management framework for safety critical rail infrastructure. The outputs of the CBA undertaken during the CCA option selection should determine monitoring and evaluation requirements based upon the anticipated NbS ecosystem benefits and disservices identified. The ongoing performance monitoring during the operation and maintenance of the NbS intervention and rail infrastructure can be used to measure the actual versus predicted effectiveness of the NbS. Roles and responsibilities for monitoring and evaluation activities shall be formalised via an ***Interface Agreement***. Feedback and learning shall be recorded and shared for consideration when considering the implementation of future NbS installations.
Indicator 7.2	**A monitoring and evaluation plan is developed and implemented throughout the intervention lifecycle**	Refer to the above response provided for Indicator 7.1, the monitoring and evaluation of NbS has been integrated with that undertaken during the routine inspection and maintenance of rail infrastructure.

Reference	NbS Principle (Cohen-Shacham et al., 2016), Global Standard Criterion or Indicator (IUCN, 2020)	The relevance and alignment (or otherwise) of the framework to implement NbS as CCA for rail (Figure 5-4) with each NbS Principle/Criterion/Indicator
Indicator 7.3	**A framework for iterative learning that enables adaptive management is applied throughout the intervention lifecycle**	The inclusion of feedback loops has been a key consideration of the framework, enabling the recording and provision of feedback on the management of NbS during its Design, Installation, long-term Operation & Maintenance stages and upon its Decommissioning. The continuous monitoring and evaluation of the NbS will trigger adaptative management responses when required. The framework specifically requires the recording of NbS performance outputs throughout its lifecycle so that data and learning may be considered in future CCA selection activities and in the application of future NbS interventions.
Criterion 8	**NbS are sustainable and mainstreamed within an appropriate jurisdictional context**	The framework embeds NbS implementation into the holistic risk and lifecycle management of rail infrastructure. This framework also seeks to mainstream CCRA within business-as-usual rail industry process, regardless of whether this results in the selection of NbS, hybrid grey-green or traditional grey engineered interventions.
Principle 8	NbS are an integral part of the overall design of policies, and measures or actions, to address a specific challenge.	

Reference	NbS Principle (Cohen-Shacham et al., 2016), Global Standard Criterion or Indicator (IUCN, 2020)	**The relevance and alignment (or otherwise) of the framework to implement NbS as CCA for rail (**Figure 5-4**) with each NbS Principle/Criterion/Indicator**
Indicator 8.1	**The NbS design, implementation and lessons learnt are shared to trigger transformative change**	Multiple feedback loops have been incorporated within the framework, including specific steps to record and share learning from NbS implementation at each stage of the NbS/rail infrastructure lifecycle, with the intention of achieving a key goal output of the framework, aiding the further ruse of NbS as CCA for rail. This may include the scaling up and/or replication of an NbS concept at a new location. The formal recording of outputs at each stage of, and the involvement of stakeholders throughout the framework lifecycle means that data can be captured in a format to inform future CBA and decision-making processes.
Indicator 8.2	**The NbS informs and enhances facilitating policy and regulation frameworks to support its uptake and mainstreaming**	The overarching aim of the framework is to aid the uptake and mainstreaming of NbS for CCA in rail infrastructure. ***Pro-NbS planning policy and legislation*** is included as a key framework input and it is hoped that the success of and/or lessons learned through NbS implementation, combined with the development of NbS selection criteria and guidance (during the ***NbS selected as Climate Change Adaptation measure*** phase) obtained through the use of this framework will facilitate the progression of further future policy and legislation which encourage, or mandate, NbS selection for certain scenarios. NbS implementation on railway infrastructure will ultimately be governed by overarching rail infrastructure risk management, however; safety will always be the top priority. The

Reference	NbS Principle (Cohen-Shacham et al., 2016), Global Standard Criterion or Indicator (IUCN, 2020)	The relevance and alignment (or otherwise) of the framework to implement NbS as CCA for rail (Figure 5-4) with each NbS Principle/Criterion/Indicator
		suitability of NbS as a CCA will be assessed from this standpoint during the CCA option selection process which may see NbS ruled out as a safe and reasonably practicable measure on safety and/or on the grounds of other railway operational requirements.
Indicator 8.3	**Where relevant, the NbS contributes to national and global targets for human well-being, climate change, biodiversity and human rights, including the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP)**	The contribution to the UN SDGs of NbS use for CCA on rail infrastructure is discussed in Chapter 2 and Chapter 5. ***Rail organisational sustainability policy, objectives and targets*** are a framework input, and many of these vehicles are linked to SDGs and national social, economic and ecological targets and commitments. The aim of the framework is to provide a CCA response, therefore contributing to CCA targets, whilst use of green NbS measures to provide CCA supports climate change mitigation and other social and ecological targets. Regarding human rights and consultation with indigenous peoples, as per Criteria 1 and 5 and Principle 6, this may not always be guaranteed due to the statutory powers of rail infrastructure/landowners and their overriding concerns for public safety which may preclude consultation with and/or permission being obtained from neighbouring landowners and communities. The framework does however advocate the co-development of CCA solutions with adjacent owners, which should be undertaken whenever reasonably practicable.

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