Transportation Research Part D 113 (2022) 103529

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Barriers and tools for implementing Nature-based solutions for rail climate change adaptation

Lorraine Blackwood [*], Fabrice G. Renaud

School of Interdisciplinary Studies, University of Glasgow, Dumfries, UK

A R T I C L E I N F O

Keywords:
Nature-based Solutions
Rail infrastructure
Climate change adaptation
Climate change risk assessment

A B S T R A C T

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.

1. Climate change impacts on rail infrastructure and adaptation options

Globally, transport infrastructure are exposed to hydro-meteorological hazards (HMH) (Thornes, 1992; Jaroszweski et al., 2010) 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, IPCC, 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 and 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 (Davies and Hockridge, 2014; Blackwood et al., 2022).

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., 2020). 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

---

[*] Corresponding author.
E-mail address: l.blackwood.2@research.gla.ac.uk (L. Blackwood).

https://doi.org/10.1016/j.trd.2022.103529
Received 6 May 2022; Received in revised form 21 October 2022; Accepted 4 November 2022

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 and 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 (Kabisch et al., 2016; Davies and Lafortezza, 2019; Frantzeskaki et al., 2019; Sarabi et al., 2019, 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.

2. Methodology

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.

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.

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 Fig. 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.

3. Results: Identified barriers to the uptake of NbS as climate change adaptation measures for rail infrastructure

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, 2014, 2020a). 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, 2020b). 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, 2020a). 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 (HM Government, 2017). Similarly, careful consideration would have to be given to the location of protection forests planted in response to increased threat of landslides and earthworks 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 bush fire it is recommended that vegetation possessing high moisture and low volatile

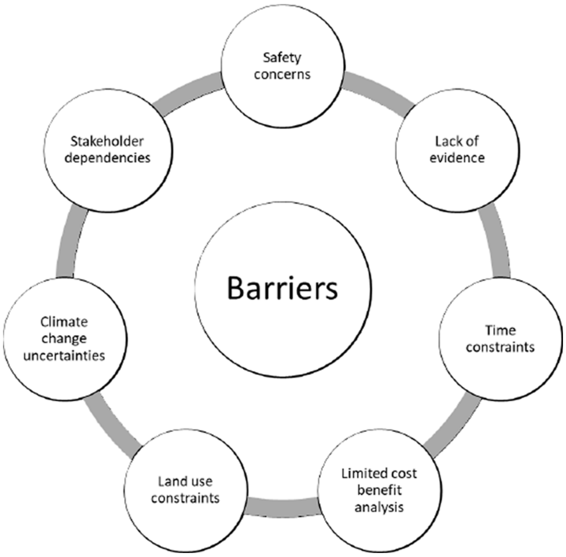


Fig. 1. Barriers to the uptake of Nature-based Solutions as climate change adaptation measures for railway infrastructure, as emerging from the literature review.

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 and 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, 2020c). 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, 2020d). 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, 2020d). 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 and 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 and 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 (Transport for New South Wales, 2016; Queensland Government, 2020; Network Rail, 2021). 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 (Wang et al., 2020a), 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. (2017) 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.

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.

3.2. 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 and 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 (The Royal Society, 2014; 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 (Sarabi et al., 2019; Collier, 2021). 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 (Sudmeier-Rieux et al., 2021; Anderson et al., 2022).

With an absence of legal instruments and the currently limited dissemination of standards and guidelines (Estrella and 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; Kabisch et al., 2016; 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 and Hockridge, 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 and Hockridge, 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., 2020b).

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 (The Royal Society, 2014; Albert et al., 2019; Sarabi et al., 2019). 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 and Grimm, 2020). Whilst the resultant impacts to rail networks will disrupt a large number of people in cities (Koetse and 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 m of sea wall at Dawlish in the UK in 2014 (see Fig. 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).

(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 required 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 (HM 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, 2021), particularly those around "Life on Land" and "Industries, Innovation and Infrastructure" (United Nations Global Compact, 2019).

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.

Fig. 2. Collapse of Dawlish sea wall in February 2014.

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, 2020a, 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, 2020a). 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 (Lindgren et al., 2009; Palko and Lemmen, 2017; Climate ADAPT, 2019). 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 Europe, 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, 2020a). 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, 2020a). 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. (2016, p. 30) 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. 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, 2020c). Consultation with these stakeholders would support the implementation of the semi-open corridor approach introduced in Section 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 and Lemmen, 2017). Casello and 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).

3.4.1.1. 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 and Lafortezza, 2019). Grey infrastructural measures are firmly established in some settings and influence institutional protocols (Seddon et al., 2020a), 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 and 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 and 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 (The Royal Society, 2014; Ruangpan et al., 2020). 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., 2020a), 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., 2017).

3.4.1.2. *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 and 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 many NbS-related resources such as OPERAs Project (2012), European Centre for Nature Conservation (2017), GrowGreen (2017), Nature4Cities (2017), University of Copenhagen (2017), NAIAD (2021), Naturvation (2021), Oppla (2021), UNaLab (2021), and 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.

3.5. 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 and Chapman, 2012). There is, however, a lack of studies examining climate threats within the rail sector (Blackwood et al., 2022; Wang et al., 2020b). 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 and Chapman, 2012). Referring to the relationships between HMH and rail infrastructure (see Blackwood et al., 2022) and the CCRA process outlined in Section 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).

3.6. 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 (Kumar et al., 2020; Albert et al., 2019). 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, 2014; Sarabi et al., 2019; Seddon and Daniels, 2020a; 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, 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.

3.7. 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., 2020a). Whilst an abundance of historical cost and benefit data exists for grey infrastructure (Bertule, 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, 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, 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, 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 and 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 (Secretariat of the Convention on Biological Diversity, 2009; Jones et al., 2012; Kabisch et al., 2016). 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, 2019; Kabisch, 2016; Ruangpan, 2020; Seddon and Daniels, 2020a). 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., 2020a).

Sustainability rating tools, such as CEEQUAL (Building Research Establishment, 2021) and the Infrastructure Sustainability Council's (ISC) Rating Scheme (ISC, 2021), 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" (ISC, 2021, p. 36), and specifically, that Urban and Landscape Design Plans must consider green infrastructure integration, biodiversity and habitat connectivity (ISC, 2021), 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" (ISC, 2021, 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.

3.8. Summary of potential aids to NbS uptake in rail infrastructure

Fig. 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., 2020c, 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,

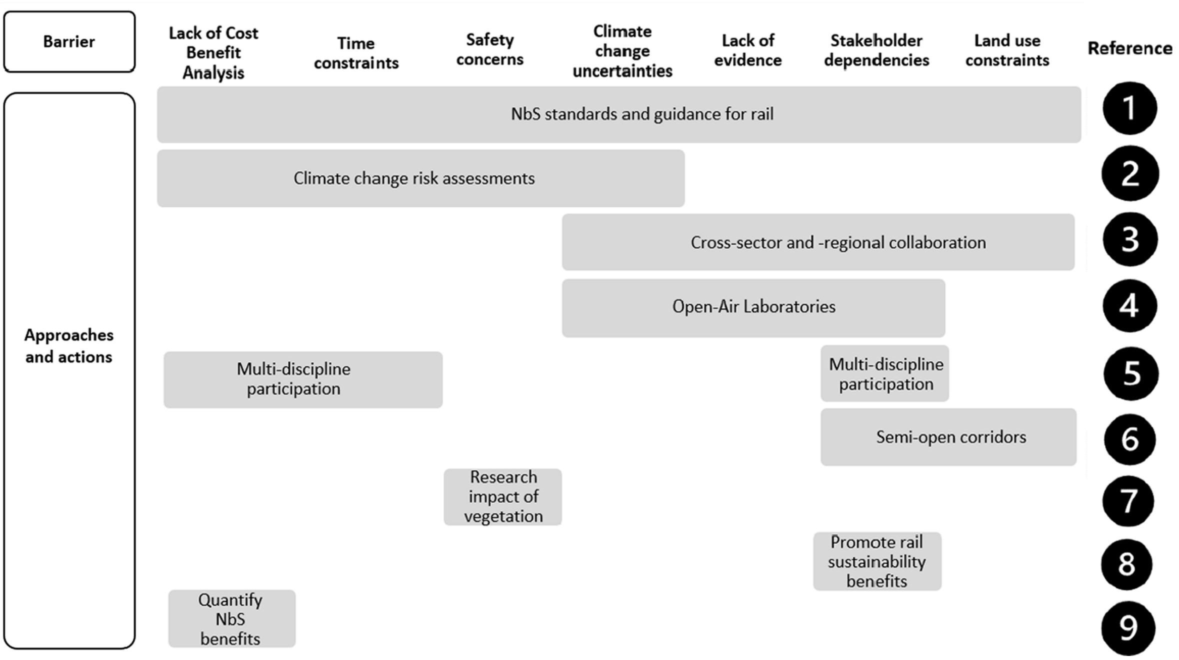
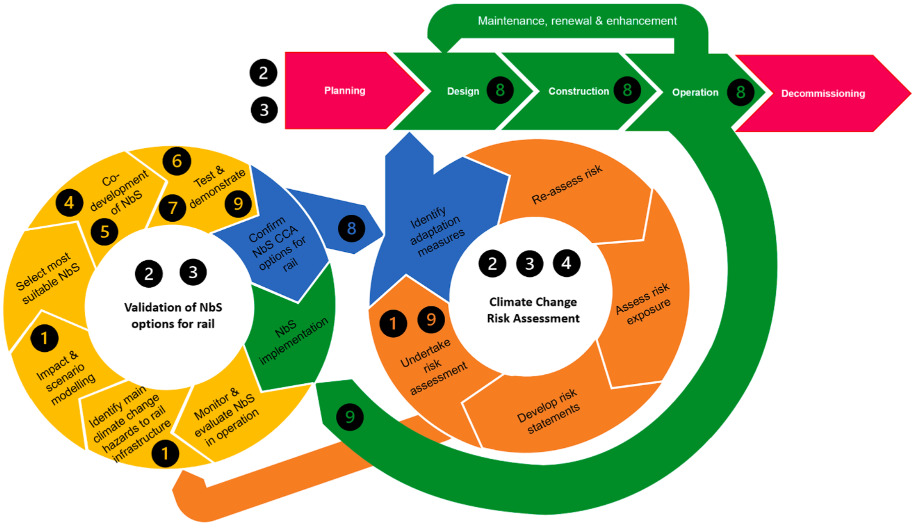
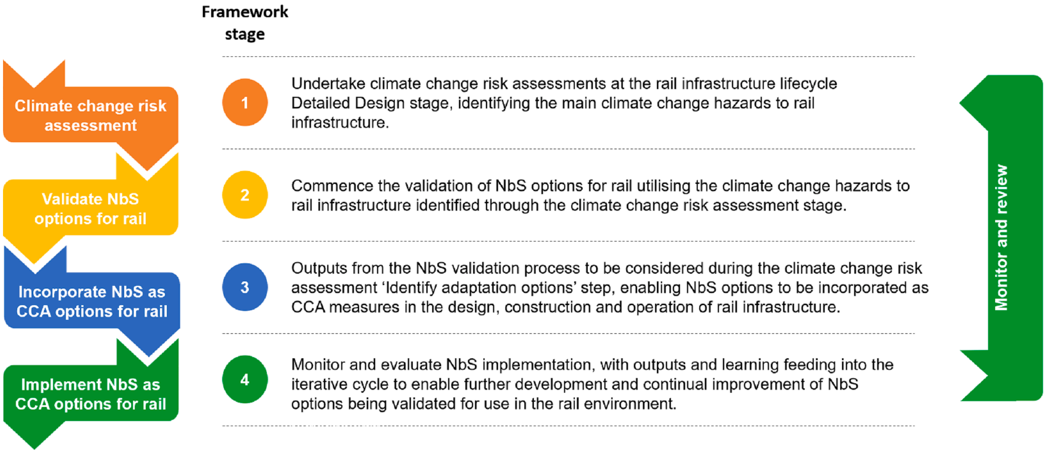


Fig. 3. Approaches and actions that may support the implementation of nature-based solutions as climate change adaptation measures for railway infrastructure.

Key

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 (2020)
🟦	Incorporation of NbS as CCA options for rail	Author
🟩	Implementation of NbS in rail infrastructure	Author
❶ to ❾	Approach/action reference number	Figure 3 and Table 1





Framework stage	
1	Undertake climate change risk assessments at the rail infrastructure lifecycle Detailed Design stage, identifying the main climate change hazards to rail infrastructure.
2	Commence the validation of NbS options for rail utilising the climate change hazards to rail infrastructure identified through the climate change risk assessment stage.
3	Outputs from the NbS validation process to be considered during the climate change risk assessment 'Identify adaptation options' step, enabling NbS options to be incorporated as CCA measures in the design, construction and operation of rail infrastructure.
4	Monitor and evaluate NbS implementation, with outputs and learning feeding into the iterative cycle to enable further development and continual improvement of NbS options being validated for use in the rail environment.

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

Table 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 Fig. 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, 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.
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 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;

(*continued on next page*)

Table 1 (*continued*)

Reference Number	Proposed Approach/Action	Description
		this could be tackled per railway 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.

- Whilst some literature acknowledges the need for rail CCA there are no details of the interventions required (Armstrong et al., 2017).

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 Fig. 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., Network Rail, 2017; Wordsworth, 2019; Government of South Australia, 2020; California High-Speed Rail Authority, 2021) 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 Fig. 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 Section 3. The approaches and actions, numbered 1–9 in Fig. 4, are labelled as per Table 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 completion of a CCRA represents a critical step for CCA to be included in the lifecycle of rail infrastructure (Fig. 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. Fig. 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 (Transport for New South Wales, 2016; Network Rail, 2021), and a Preliminary Design CCRA evaluation can enable the comparison of risk exposures between options (Queensland Government, 2020; Network Rail, 2021). The later "Detailed Design" stage is, however, highlighted as the key intervention point, (Transport for New South Wales, 2016; Queensland Government, 2020; Network Rail, 2021).

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 Fig. 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 Fig. 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 Fig. 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.

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.

CRediT authorship contribution statement

Lorraine Blackwood: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Fabrice G. Renaud:** Conceptualization, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

We thank Steven Gillespie for his support with this study and assistance in reviewing previous drafts of the manuscript.

Funding.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

Albert, C., Schroter, B., Haase, D., Brillinger M., Henze, J., Herrmann, S., Gottwald, S., Guerrero, P., Nicolas, C. and Matzdorf, B. (2019) 'Addressing societal challenges through nature-based solutions: How can landscape planning and governance research contribute?', *Landscape and Urban Planning*, 182, pp. 12–21. Available at: 10.1016/j.landurbplan.2018.10.003.

An, M., Lin, W., Huang, S., 2013. *An Intelligent Railway Safety Risk Assessment Support System for Railway Operation and Maintenance Analysis.* The Open Transportation Journal 7 (1), 27–42.

Anderson, C.C., Renaud, F.G., Hanscomb, S., Gonzalez-Ollauri, A., 2022. *Green, hybrid, or grey disaster risk reduction measures: What shapes public preferences for nature-based solutions?* Journal of Environmental Management 310. https://doi.org/10.1016/j.jenvman.2022.1147277.

Armstrong, J., Preston, J. and Hood, I. (2017) 'Adapting railways to provide resilience and sustainability', *Proceedings of the Institution of Civil Engineers: Engineering Sustainability*, 170(ES4), pp. 225–234. Available at: 10.1680/jensu.15.00017.

Standards Australia (2013) *Australian Standard ® Climate change adaptation for settlements and infrastructure - A risk based approach.* Available at: www.standards.org.au.

Benedetti, Y. and Morelli, F. (2017). *Spatial mismatch analysis among hotspots of alien plant species, road and railway networks in Germany and Austria, PLoS ONE*, 12(8). Available at: 10.1371/journal.pone.0183691.

Bertule, M., et al., 2014. *Green Infrastructure Guide for Water Management: Ecosystem-based management approaches for water-related infrastructure projects.* United Nations Environment Programme.

Blackwood, L., Renaud, F.G., Gillespie, S., 2022. *Nature-based solutions as climate change adaptation measures for rail infrastructure.* Nature-Based Solutions, 100013. Available at: 10.1016/j.nbsj.2022.100013.

Blair, J., Roldan, C., Ghosh, S. and Yung, S-H. (2017) 'Greening Rail Infrastructure for Carbon Benefits', in *Procedia Engineering*, pp. 1716–1724. Available at: 10.1016/j.proeng.2017.04.334.

Building Research Establishment, 2021. *CEEQUAL*, https://www.ceequal.com/. (Accessed: 26 September 2021).

Butchart, S.H.M., et al., 2010. *Global Biodiversity: Indicators of Recent Declines.* Science 328 (5982), 1164–1168. Available at: 10.1126/science.1186777.

California High-Speed Rail Authority, 2021. *The Stage Gate Process*, https://hsr.ca.gov/about/high-speed-rail-business-plans/2020-business-plan/chapter-6/. (Accessed: 7 August 2021).

Casello, J., Towns, W., 2017. *Urban*. In: Palko, K., Lemmen, D.S. (Eds.), Climate risks and adaptation practices for the Canadian transportation sector 2016. Government of Canada, Ottawa, ON, pp. 264–309.

Castro-Fresno, D., Andrés-Valeri, V.C., Sañudo-Fontaneda, L.A., Rodriguez-Hernandez, J., 2013. *Sustainable drainage practices in Spain, specially focused on pervious pavements*. Water (Switzerland). MDPI AG 67–93. Available at: 10.3390/w5010067.

Climate ADAPT (2019) *Operation and construction measures for ensuring climate-resilient railway infrastructure*. Available at: https://climate-adapt.eea.europa.eu/metadata/adaptation-options/operation-and-construction-measures-for-ensuring-climate-resilient-railway-infrastructure (Accessed: 14 August 2021).

Chausson, A., Turner, B., Seddon, D., Chabaneix, N., Girardin, C., Kapos, V., Key, I., Roe, D., Smith, A., Woroniecki, S., Seddon, N., 2020. *Mapping the effectiveness of nature-based solutions for climate change adaptation*. Global Change Biology 1–22. Available at: 10.1111/gcb.15310.

Cohen-Shacham, E., Walters, G., Janzen, C., Maginnis, S., 2016. 'Nature-based Solutions to address global societal challenges', *Nature-based solutions to address global societal challenges* [Preprint]. Available at. https://doi.org/10.2305/iucn.ch.2016.13.en.

Collier, M.J. (2021). *Are field boundary hedgerows the earliest example of a nature-based solution? Environmental Science and Policy*. Elsevier Ltd, pp. 73–80. Available at: 10.1016/j.envsci.2021.02.008.

CSIRO (2021) *Adaptation pathways: meeting the challenges of global change*, https://www.csiro.au/en/research/environmental-impacts/climate-change/Adaptation-pathways. (Accessed 4 September 2021).

Cowling, R.M., Egoh, B., Knight, A.T., O'Farrell, P.J., Reyers, B., Rouget, M., Roux, D.J., Welz, A., Wilhelm-Rechman, A., 2008. An operational model for mainstreaming ecosystem services for implementation. Proceedings of the National Academy of Sciences of the United States of America 105 (28), 9483–9488.

Davies, L., Bell, J., Bone, J., Head, M., Hill, L., Howard, C., Hobbs, S., Jones, D., Power, S., Rose, N., Ryder, C., Seed, L., Stevens, G., Toumi, R., Voulvoulis, N., White, P., 2011. *Open Air Laboratories (OPAL): A community-driven research programme*. Environmental Pollution 2203–2210. Available at: 10.1016/j.envpol.2011.02.053.

Davies, H.J. and Hockridge, B. (2014) *Natural England Commissioned Report NECR168, NEWP32 Transport green corridors: literature review, options appraisal and opportunity mapping*.

Davies, C., Lafortezza, R., 2019. *Transitional path to the adoption of nature-based solutions*. Land Use Policy 80, 406–409. Available at: 10.1016/j.landusepol.2018.09.020.

De Bruin, K., Delink, R., Ruijs, A., Bolwidt, L., Van Buuren, A., Graveland, J., De Groot, R., Kuikman, P., Reinhard, S., Roetter, R., Tassone, V., Verhagen, A., Van Ierland, E, 2009. *Adapting to climate change in The Netherlands: An inventory of climate adaptation options and ranking of alternatives*. Climatic Change 95, 23–45. Available at: 10.1007/s10584-009-9576-4.

Debele, S.E., Kumar, P., Sahani, J., Marti-Cardona, B., Mickovski, S., Leo, L., Porcu, F., Bertini, F., Montesi, D., Vojinovic, Z., Di Sabatino, S., 2019. *Nature-based solutions for hydro-meteorological hazards: Revised concepts, classification schemes and databases*. Environmental Research 179. https://doi.org/10.1016/j.envres.2019.108799.

Denjean, B., Altamirano, M., Graveline, N., Giordano, R., Van der Keur, P., Moncoulon, D., Weinberg, J., Manez Costa, M., Kozinc, Z., Mulligan, M., Pengal, P., Matthews, J., van Cauwenbergh, N., Lopez Gunn, E., Bresch, D., 2017. Natural Assurance Scheme: A level playing field framework for Green-Grey infrastructure development. Environmental Research 159, 24–38. Available at: 10.1016/j.envres.2017.07.006.

Doll, C., Trinks, C., Sedlacek, N., Pelikan, V., Comes, T., Schultmann, F., 2013. 'Adapting rail and road networks to weather extremes: Case studies for southern Germany and Austria', *Natural Hazards* [Preprint]. Available at. https://doi.org/10.1007/s11069-013-0969-3.

Driscoll, P.A. (2014) 'Breaking Carbon Lock-In: Path Dependencies in Large-Scale Transportation Infrastructure Projects', *Planning Practice and Research*, 29(3), pp. 317–330. Available at: 10.1080/02697459.2014.929847.

Eisenack, K., Stecker, R., Reckien, D., Hoffmann, E., 2012. Adaptation to climate change in the transport sector: A review of actions and actors. Mitigation and Adaptation Strategies for Global Change 451–469. Available at: 10.1007/s11027-011-9336-4.

HM Government (2019). *Enhancing Biodiversity and Wildlife on the Lineside*. Department for Transport. July 2019.

Estrella, M. and Saalismaa, N. (2013) 'Ecosystem-based disaster risk reduction (Eco-DRR): An Overview', in F.G. Renaud, K. Sudmeier-Rieux, and M. Estrella (eds) *The role of ecosystems in disaster risk reduction*. United Nations University Press, p. 476.

European Centre for Nature Conservation (2017) *OpenNESS*. Available at: http://www.openness-project.eu/ (Accessed: 31 July 2021).

European Commission Directorate-General for Regional and Urban Policy (2018) *Climate change adaptation of major infrastructure projects*. Brussels. Available at: 10.2776/758755.

European Commission. Directorate-General for Research and Innovation, 2015. Towards an EU Research and Innovation policy agenda for Nature-Based Solutions & Re-Naturing Cities: Final Report of the Horizon 2020 Expert Group on 'Nature-Based Solutions and Re-Naturing Cities' : (full version). Publications Office of the European Union, Brussels.

Faivre, N., Fritz, M., de Boissezon, B., Vandewoestijne, S., 2017. Nature-Based Solutions in the EU: Innovating with nature to address social, economic and environmental challenges. Environmental Research 159, 509–518. https://doi.org/10.1016/j.envres.2017.08.032.

Fink, H.S., 2016. 'Human-nature for Climate Action: Nature-Based Solutions for Urban Sustainability', *Sustainability (Switzerland)*, 8(3). Available at. https://doi.org/10.3390/su8030254.

Fisk, G., Tonmoy, F., Rissik, D., 2019. 'Climate Change and Coastal Transport Infrastructure - How Do We Keep Australia Moving?', in *Lecture Notes in Mechanical Engineering*. Available at. https://doi.org/10.1007/978-3-319-95711-1_17.

Frantzeskaki, N., McPhearson, T., Collier, M., Kendal, D., Bulkeley, H., Dumitru, A., Walsh, C., Noble, K., Van Wyk, E., Ordonez, C., Oke, C., Pinter, L., 2019. Nature-based solutions for urban climate change adaptation: Linking science, policy, and practice communities for evidence-based decision-making. BioScience 69 (6), 455–466. Available at: 10.1093/biosci/biz042.

Government of South Australia Department for Infrastructure and Transport (2020) *Project Controls Master Specification PC-RW10 Railways Management Planning*.

URBAN GreenUP (2021) *URBAN GreenUP*. Available at: https://www.urbangreenup.eu/ (Accessed: 31 July 2021).

GrowGreen (2017) *GrowGreen*. Available at: http://growgreenproject.eu/ (Accessed: 31 July 2021).

HM Government (2017) *UK Climate Change Risk Assessment 2017*.

Hobbie, S.E., Grimm, N.B., 2020. Nature-based approaches to managing climate change impacts in cities. *Philosophical Transactions of the Royal Society B: Biological Sciences*. Royal Society Publishing. Available at. https://doi.org/10.1098/rstb.2019.0124.

Hooper, E. and Chapman, L. (2012) 'The impacts of climate change on national road and rail networks', in *Transport and Sustainability*. Emerald Group Publishing Ltd., pp. 105–136. Available at: 10.1108/S2044-9941(2012)0000002008.

Hutley, N., Hartford Davis, S., 2019. *Climate Change and Directors' Duties*. Supplementary Memorandum of Opinion.

Infrastructure Sustainability Council, 2021. *Infrastructure Sustainability Rating Scheme: Technical Manual, Design & As-Built, Version 2.1*. Available at: www.isca.org.au. (Accessed 26 September 2021).

The British Standards Institution (2019) *Adaptation to climate change – Principles, requirements and guidelines (ISO 14090:2019)*. BSI Standards Limited.

IUCN (2020) *IUCN Global Standard for Nature-based Solutions*. IUCN, International Union for Conservation of Nature. Available at: 10.2305/IUCN.CH.2020.09.en.

IPCC , 2021. Summary for Policymakers. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (Eds.)]. Cambridge University Press. In press.

IPCC , 2022. Summary for Policymakers [H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem (Eds.)]. Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (Eds.)]. Cambridge University Press.

Jaroszweski, D., Chapman, L., Petts, J., 2010. Assessing the potential impact of climate change on transportation: the need for an interdisciplinary approach. Journal of Transport Geography 18 (2), 331–335. Available at: 10.1016/j.jtrangeo.2009.07.005.

Jones, H.P., Hole, D.G., Zavaleta, E.S., 2012. 'Harnessing nature to help people adapt to climate change', *Nature*. Climate Change 2 (7), 504–509. Available at: 10.1038/nclimate1463.

Kabisch, N., Frantzeskaki, N., Paulett, S., Naumann, S., Davis, M., Artmann, M., Hasse, D., Knapp, S., Korn, H., Stadler, J., Zaunberger, K., Bonn, A., 2016. Nature-based solutions to climate change mitigation and adaptation in urban areas: Perspectives on indicators, knowledge gaps, barriers and opportunities for action. Ecology and Society 21 (2), (39).

Koetse, M.J. and Rietveld, P. (2012) 'Adaptation to Climate Change in the Transport Sector', *Transport Reviews*, 32(3), pp. 267–286. Available at: 10.1080/01441647.2012.657716.

Kabisch, N., Korn, H., Stadler, J., Bonn, A., 2017. *Nature-based Solutions to Climate Change Adaptation in Urban Areas*. Springer Open.

Kumar, P., Debele, S., Sahani, J., Aragao, L., Barisani, F., Basu, B., Bucchignani, E., Charizopoulos, N., Sabatino, S., Domeneghetti, A., Edo, A., Finer, L., Gallotti, G., Juch, S., Leo, L., Loupis, M., Mickovski, S., Panga, D., Pavlova, I., Pilla, F., Prats, A., Renaud, F., Rutzinger, M., Basu, A., Shah, M., Soini, K., Stefanopoulou, M., Toth, E., Ukonmaanaho, L., Vranic, S., Zieher, T., 2020. 'Towards an operationalisation of nature-based solutions for natural hazards', *Science of the Total Environment*, 731. Available at. https://doi.org/10.1016/j.scitotenv.2020.138855.

Lavorel, S., Colloff, M., McIntyre, S., Doherty, M., Murphy, H., Metcalfe, D., Dunlop, M., Williams, R., Wise, R., Williams, K., 2015. Ecological mechanisms underpinning climate adaptation services. Global Change Biology 21 (1), 12–31. Available at: 10.1111/gcb.12689.

Lin, B.B., Meyers, J., Beaty, R., Barnett, G., 2016. 'Urban green infrastructure impacts on climate regulation services in Sydney, Australia', *Sustainability*, 8(788). Available at. https://doi.org/10.3390/su8080788.

Lindgren, J., Jonsson, D.K., Carlsson-Kanyama, A., 2009. Climate Adaptation of Railways: Lessons from Sweden. European Journal of Transport and Infrastructure Research 9 (2), 164–181. Available at: 10.18757/ejtir.2009.9.2.3295.

Martani, C., Papathanasiou, N., Adey T., B., 2017. A Review of the State-of-the-Art in Railway Risk Management. International Journal of Railway 10 (1). https://doi.org/10.7782/IJR.2017.10.1.005.

McVittie, A., Cole, L., Wreford, A., Sgobbi, A., Yordi, B., 2018. Ecosystem-based solutions for disaster risk reduction: Lessons from European applications of ecosystem-based adaptation measures. International Journal of Disaster Risk Reduction 32, 42–54. Available at: 10.1016/j.ijdrr.2017.12.014.

Millennium Ecosystem Assessment (2005) *Ecosystems and human well-being: Synthesis*. Washington: Island Press.

NAIAD (2021) *Nature Insurance Value: Assessment and Demonstration*. Available at: http://naiad2020.eu/ (Accessed: 31 July 2021).

National Research Council (2008) *Potential impacts of climate change on U.S. Transportation: Special Report 290*. Washington, DC. Available at: 10.17226/12179.

Nature4Cities (2017) *Nature4Cities*. Available at: https://www.nature4cities.eu/ (Accessed: 31 July 2021).

Naturvation (2021) *Naturvation*. Available at: https://naturvation.eu/ (Accessed: 31 July 2021).

Network Rail, 2015. Climate Change Adaptation Report 2015.

Network Rail, 2017. *Level 2 Business Process: Governance for Railway Investment Projects (GRIP)*. Network Rail, London.

OECD, 2018. Climate-resilient Infrastructure. OECD Environment Policy Paper No. 14.

Office of the National Rail Safety Regulator (2020) *Safety Management System Modules Element 16 - Risk Management*.

OPERAs Project (2012) *OPERAs Project*. Available at: http://operas-project.eu/ (Accessed: 31 July 2021).

OPPLA (2021) *Transitioning towards urban resilience and sustainability (TURAS)*, https://oppla.eu/groups/turas-group/about-turas. Available at: *https://oppla.eu/groups/turas-group/about-turas* (Accessed: 31 July 2021).

Pakzad, P. and Osmond, P. (2015). *A Conceptual Framework for Assessing Green Infrastructure Sustainability Performance in Australia*. State of Australian Cities. Gold Coast . Available at: 10.13140/RG.2.1.3991.9448.

Palko, K., Lemmen, D.S. (Eds.), 2017. *Climate risks and adaptation practices for the Canadian transportation sector 2016*. Government of Canada, Ottawa, ON.

Perales-Momparler, S., Andres-Domenech, I., Hernandez-Crespo, C., Valles-Moran, F., Martin, M., Escuder-Bueno, I., Andreu, J., 2017. The role of monitoring sustainable drainage systems for promoting transition towards regenerative urban built environments: a case study in the Valencian region, Spain. Journal of Cleaner Production 163, S113–S124. Available at: 10.1016/j.jclepro.2016.05.153.

Pierson, T.C., Wood, N.J., Driedger, C.L., 2014. Reducing Risk from Lahar Hazards Concepts Case Studies, and Roles for Scientists. Journal of Applied Volcanology 3 (16).

Pietras-Couffignal, K., Below, M., Yimazer, P., Nolte, R. and Schuh, T. (2021) *Future vegetation control of European Railways State-of-the-art report*. Paris.

Queensland Government (2020). Department of Transport and Main Roads *Climate Change Risk and Adaptation Assessment Framework for Infrastructure Projects*.

Quinn, A.D., Ferranti, E., Hodgkinson, S., Jack, A., Beckford, J., Dora, J., 2018. 'Adaptation becoming business as usual: A framework for climate-change-ready transport infrastructure', *Infrastructures*, 3(10). Available at. https://doi.org/10.3390/infrastructures3020010.

Quinn, A., Beckford, J. and Dora, J. (2017) *Rail Adapt - Adapting the railway for the future*. Paris.

Rail Safety and Standards Board Ltd (2021) *Rail Risk Toolkit*, https://www.rssb.co.uk/safety-and-health/improving-safety-health-and-wellbeing/Rail-Risk-Toolkit. (Accessed 4 September 2021).

Network Rail (2014) 'Identifying Invasive & Injurious Plants'. Available at: https://safety.networkrail.co.uk/wp-content/uploads/2016/01/Share-With-Pride-Invasive-Injurious-Plants-July-14.pdf (Accessed: 6 November 2021).

Network Rail (2019a) *Five years since we opened Dawlish*, *https://www.networkrail.co.uk/stories/five-years-since-we-reopened-dawlish/*. Available at: https://www.networkrail.co.uk/stories/five-years-since-we-reopened-dawlish/ (Accessed: 27 March 2021).

Network Rail (2019b) *Scotland's Railway CP6 Weather Resilience and Climate Change Adaptation Plans 2019-2024*.

Network Rail (2020a). Level 2 Manual: Lineside Vegetation Management Manual. Ref: NR/L2/OTK/5201.

Network Rail (2020b) *Anglia 2019 – 2024 Route Weather Resilience and Climate Change Adaptation Plan*.

Network Rail (2020c) *London North East and East Midlands Route CP6 Weather Resilience and Climate Change Adaptation Plans 2019-2024*.

Network Rail (2020d) 'NW&C Region CP6 Weather Resilience and Climate Change Adaptation Plan'.

Network Rail (2021) *Weather resilience & climate change impact assessment [Guidance Note, Weather Resilience and Climate Change Adaptation]*.

Reddy, S.M.W., McDonald, R., Maas, A., Rogers, A., Girvetz, E., North, J., Molnar, J., Finley, T., Leathers, G., DiMuro, J., 2015. Finding solutions to water scarcity: Incorporating ecosystem service values into business planning at The Dow Chemical Company's Freeport, TX facility. Ecosystem Services 12, 94–107. Available at: 10.1016/j.ecoser.2014.12.001.

Rizvi, A.R., Baig, S. and Verdone, M. (2015) Ecosystem Based Adaptation: Knowledge Gaps in Making an Economic Case for Investing in Nature Based Solutions for Climate Change. Gland, Switzerland.

Ruangpan, L., Vojinovic, Z., Di Sabatino, S., Leo, L., Capobianco, V., Oen, A., McClain, M., Lopez-Gunn, E., 2020. Nature-based solutions for hydro-meteorological risk reduction: a state-of-the-art review of the research area. Natural Hazards and Earth System Sciences 20 (1), 243–270. Available at: 10.5194/nhess-20-243-2020.

Sahani, J., Kumar, P., Debele, S., Spyrou, C., Loupis, M., Aragao, L., Porcu, F., Shah, M., Di Sabatino, S., 2019. Hydro-meteorological risk assessment methods and management by nature-based solutions. Science of the Total Environment. Elsevier B.V. Available at: 10.1016/j.scitotenv.2019.133936.

Sanderson, M.G., Hanlon, H.M., Palin, J., Quinn, A.D., Clark, R.T., 2016. Analogues for the railway network of Great Britain. Meteorological Applications 23, 731–741. https://doi.org/10.1002/met.1597.

Sarabi, S.E., Han, Q., de Vries, B., Wending, L., 2019. Key enablers of and barriers to the uptake and implementation of nature-based solutions in urban settings: A review. Resources. Available at. https://doi.org/10.3390/resources8030121.

Sarabi, S., Han, Q., Romme, A., de Vries, B., Valkenburg, R., den Ouden, E., 2020. 'Uptake and implementation of Nature-Based Solutions: An analysis of barriers using Interpretive Structural Modeling', *Journal of Environmental Management*, 270. Available at. https://doi.org/10.1016/j.jenvman.2020.110749.

Secretariat of the Convention on Biological Diversity (2009) *Connecting biodiversity and climate change mitigation and adaptation: report of the Second Ad Hoc Technical Expert Groupon Biodiversity and Climate Change*. Montreal, Canada. Available at: www.cbd.int.

Seddon, N., Chausson, A., Berry, P., Girardin, C., Smith, A., Turner, B., 2020. Understanding the value and limits of nature-based solutions to climate change and other global challenges. Philosophical Transactions of the Royal Society B: Biological Sciences. Royal Society Publishing. Available at. https://doi.org/10.1098/rstb.2019.0120.

Seddon, N., Daniels, E., et al., 2020a. Global recognition of the importance of nature-based solutions to the impacts of climate change. Global Sustainability 3 (e15), 1–12. Available at: 10.1017/sus.2020.8.

Shackleton, C.M., Ruwanza, S., Sinasson Sanni, G., Bennett, S., De Lacy, P., Modipa, R., Mtati, N., Sachikonye, M., Thondhlana, G., 2016. Unpacking Pandora's Box: Understanding and Categorising Ecosystem Disservices for Environmental Management and Human Wellbeing. Ecosystems 19, 587–600. Available at: 10.1007/s10021-015-9952-z.

Shah, M., Renaud, F.G., Anderson, C.C., Wild, A., Domeneghetti, A., Polderman, A., Votsis, A., Pulvirenti, B., Basu, B., Thomson, C., Panga, D., Pouta, E., Toth, E., Pilla, F., Sahani, J., Ommer, J., El Zohbi, J., Munro, K., Stefanopoulou, M., Loupis, M., Pangas, N., Kumar, P., Debele, S., Preuschmann, S., Zixuan, W., 2020. A review of hydro-meteorological hazard, vulnerability, and risk assessment frameworks and indicators in the context of nature-based solutions. International Journal of Disaster Risk Reduction. Elsevier Ltd., Available at: 10.1016/j.ijdrr.2020.101728.

Sudmeier-Rieux, K., Arce-Mojica, T., Boehmer, H., Doswald, N., Emerton, L., Friess, D., Galvin, S., Hagenlocher, M., James, H., Laban, P., Lacambra, C., Lange, W., McAdoo, B., Moos, C., Mysiak, J., Narvaez, L., Nehren, U., Peduzzi, P., Renaud, F.G., Sandholz, S., Schreyers, L., Sebesvari, Z., Tom, T., Triyanti, A., van Eijk, P., van Staveren, M., Vicarelli, M., Walz, Y., 2021. 'Scientific evidence for ecosystem-based disaster risk reduction', *Nature Sustainability* [Preprint]. Available at. https://doi.org/10.1038/s41893-021-00732-4.

Staudinger, M.D., Grimm, N., Staudt, A., Carter, B., Chaplin III, S., Kareiva, P., Ruckelshaus, M. and Stein, B. (2012) *Impacts of Climate Change on Biodiversity, Ecosystems, and Ecosystem Services: Technical Input to the 2013 National Climate Assessment.*

Thameslink Programme (2021) *CEEQUAL: Bermondsey Dive Under*, https://www.thameslinkprogramme.co.uk/case-study/ceequal-bermondsey-dive-under/. (Accesed 26 September 2021).

The Royal Society (2014) *Resilience to extreme weather*. London.

The World Bank (2008) *Biodiversity, Climate Change, and Adaptation: Nature-Based Solutions from the World Bank Portfolio*. Available at: www.worldbank.org/. (Accessed 14 January 2021).

Thornes, J.E., 1992. The impact of weather and climate on transport in the UK. Progress in Physical Geography 16 (2), 187–208.

Transport for New South Wales, 2017. Integrating Green Infrastructure Guide. Available at: www.asa.transport.nsw.gov.au.

Transport for New South Wales (2016) *TfNSW Climate Risk Assessment Guidelines 9TP-SD-081/1.0*.

Transport for New South Wales (2021) *Project delivery requirements - ISCA rating requirements, https://www.transport.nsw.gov.au/projects/project-delivery-requirements#ISCA_rating_requirements.*

Travers, E., Härdtle, W., Matthies, D., 2021. 'Corridors as a tool for linking habitats – Shortcomings and perspectives for plant conservation', *Journal for Nature Conservation*, 60. Available at. https://doi.org/10.1016/j.jnc.2021.125974.

UNaLab (2021). *UNaLab*. Available at: https://unalab.eu/en (Accessed 31 July 2021).

United Nations Economic Commission for Europe (2020) *Climate Change Impacts and Adaptation for Transport Networks and Nodes*.

United Nations Global Compact (2019) *Nature-Based Solutions to Address Climate Change*. Available at: https://www.unglobalcompact.org/take-action/events/climate-action-summit-2019/nature-based-solutions (Accessed: 23 December 2021).

United Nations (2021) *Sustainable Development Goals*. Available at: https://www.un.org/sustainabledevelopment/sustainable-development-goals/ (Accessed: 2 January 2022).

University of Copenhagen (2017) *GREEN SURGE*. Available at: http://greensurge.eu/ (Accessed: 31 July 2021).

Wang, T., Qu, Z., Yang, Z. and Ng, A.K.Y. (2020b) 'How does the UK transport system respond to the risks posed by climate change? An analysis from the perspective of adaptation planning', in *Maritime Transport and Regional Sustainability*. Elsevier, pp. 85–106. Available at: 10.1016/B978-0-12-819134-7.00006-X.

Wang, T., Qu, Z., Yang, Z., Nichol, T., et al., 2020c. 'Climate change research on transportation systems: Climate risks, adaptation and planning', *Transportation Research Part D*, 88. Available at. https://doi.org/10.1016/j.trd.2020.102553.

Wang, T., Qu, Z., Yang, Z., Nichol, T., Dimitriu, D., Clarke, G., Bowden, D., Taewoo Lee, P., 2020a. *Impact analysis of climate change on rail systems for adaptation planning: A UK case*. Transportation Research Part D 83. https://doi.org/10.1016/j.trd.2020.102324.

Wordsworth, N. (2019) *GRIP (Governance for Railway Investment Projects) process explained, https://www.railengineer.co.uk/grip-governance-for-railway-investment-projects-process-explained/*. Available at: https://www.railengineer.co.uk/grip-governance-for-railway-investment-projects-process-explained/ (Accessed: 31 July 2021).

Zhang, K., Chui, T.F.M., 2019. *Linking hydrological and bioecological benefits of green infrastructures across spatial scales – A literature review*. Science of the Total Environment 646, 1219–1231. https://doi.org/10.1016/j.scitotenv.2018.07.355.