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

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ABSTRACT

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

1. Climate change impacts on rail

The transport sector is almost continuously subjected to hydro-meteorological hazards (HMH) which impact upon the efficiency of its operations [1,2] with railway infrastructure being particularly exposed and vulnerable to weather [3,4]. HMH are atmospheric, hydrological and oceanographic phenomena that may cause significant impact on human life and infrastructure; examples include floods, droughts, storm surges and temperature extremes [5,6]. Human influence on the climate system is now an established fact, with human-induced climate change increasing global surface temperatures and subsequently affecting many weather and climate extremes in every region across the globe [7]. The duration, magnitude, scale, and frequency of climate-related risks are projected to increase and worsen [8] meaning that the observed "extreme" weather of today could become the "normal" weather of tomorrow [9]. Higher average temperatures, higher sea and precipitation levels, more frequent and severe adverse hydro-meteorological events create specific risks for railway assets [10]. The exposure of railway infrastructure to these extremes, unaccounted for in its original design, may shorten its life span, pose a physical threat to the safe operation of rail services, and increase maintenance and operation costs [11]. Climate change presents a complex global challenge in managing the resilience of transport infrastructure [12] with railways needing not only to withstand current extreme weather conditions and recover from these quickly, but to also be able to continue operating in future conditions which are today regarded as extreme [13].

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

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Table 1
Key hydro-meteorological hazards to railway infrastructure, current climate adaptation measures currently in use and potential nature-based alternative and/or complements (table format adapted from [3,13,14]).

	B	C	D
Hydro-meteorological hazard	Rail infrastructure impact	Current adaptation measures	Potential NbS alternative and/or complements*
High temperatures	Rail buckling and/or associated misalignment problems [10,13,15–20]	Change rail installation procedure to increase temperature threshold for thermal expansion [10,11,21] Replacement of jointed track with continuously welded rail [21] Upgrade timber switches and crossings to concrete [22] Painting rails white in areas of known high risk to thermal expansion in direct sunlight [21]	Green corridors Vegetation shading Vegetation management – specific species selection
	Expansion of moveable assets such as swing bridges hindering operation [10,19]	Sprinkler systems [21] Replacement of bridges with heat resistant materials with lower thermal expansion coefficients [21]	
	General increase in failure rate of assets in high temperatures [3,11,13]	Use of coolers, fans and air conditioning to improve tolerance of signalling equipment [11,22,23] Double-skinned equipment casing to assist cooling [21] Sun hoods to deflect heat [22]	
	Sagging of the overhead line equipment [10,17,18]	Removal of fixed termination overhead line equipment [21] Improved balance weight and head span technologies [22]	
	Increased fire risk [15,24]	Vegetation management along tracks [4,23] Establishment of tree-free zones in rail corridor [4]	
	Permafrost degradation causing heaving, sinkholes, potholes and settlement [11,19]	Clearing snow to preserve permafrost stability [11] Installation of thermosyphons, air ducts, awnings and 'cooled roadbeds' using crushed rocks [25,26]	
Low temperatures	Rail breaks, cracks and/or associated misalignment problems [3]	Change rail installation procedure to increase temperature threshold for thermal expansion [12]	Green corridors Vegetation shading Bioengineering and biotechnical stabilisation Green walls and embankment Natural drainage solutions
	Snow blocking tracks [23,27] obscuring signals and preventing train contact with conductor rails on 'third rail' networks [21]	Use of signal hoods to prevent build-up of snow [21] Potential heating of conductor rails [21] Points heater installation [21]	
	Ice-jam flooding damaging infrastructure, particularly bridges [11]	Installation of dams, ice booms, ice-retention structures, dykes, or various channel modifications [28]	
	Tree and branch falling onto tracks due to snow loading [3,10]	Establishment of tree-free zones in rail corridor [4]	
	Icefalls in tunnels, under bridges and other structures causing damage or derailment of trains [3,23]	Review of drainage provisions for bridges and tunnels [21]	
	Frost heave of track bed and earthworks [3,11]	Capping of tunnel shafts [29]	
	Freeze-thaw damage to rock cuttings and associated landslides [3,19,23]	Rock slope stabilisation and protection [11]	

(*continued on next page*)

Table 1 (*continued*)

Hydro-meteorological hazard	B Rail infrastructure impact	C Current adaptation measures	D Potential NbS alternative and/or complements*
High precipitation	Increased risk of earthworks failure and landslides in wet weather [3,10,13,15–17,19,20]	Planting of ‘protection forests’ [23] Slope stabilisation programmes including installation of gabion walls, soil nails and sheet piles [21] Counterfort drains in slopes and crest drain refurbishment [21]	Bioengineering and biotechnical stabilisation Green walls and embankments Natural drainage solutions Protection forests
	Increased risk of bridge scour arising from flood events [3,10,13,16,17,23]	Bridge scour protection programmes [21]	
	Failure of other structure supports due to increased risk of scour [3,13,16,17]	Scour protection programmes [21]	
	Standing water fouling track ballast [11,16,17,19]	Expanding drainage capacity for infrastructure including culvert size, design for new flood event thresholds, [11,27] Increasing maintenance including clearing debris from culverts to reduce flooding [11] Installation of emergency culvert and aboiteaux [11] Installation of pumped drainage solutions [21] Reno mattresses [21]	
	Lahars causing structural damage to infrastructure [23]	Installation of containment channels and dikes [31] Revetments using riprap, gabion mattresses and concrete facings [31] Anchors, geogrids and micro-piles [31]	
Low precipitation	Increased risk of earthworks failures due to desiccation [3,10,13,19]	De-vegetation programmes [21] Re-ballasting and tamping interventions [21]	Bioengineering and biotechnical stabilisation Green walls and embankments Vegetation management – specific species selection Shelterbelts
High winds	Increased risk of leaf fall leading to low track adhesion [3]	De-vegetation programmes [21] Establishment of tree-free zones in rail corridor [4,21]	
	Damaged trees and debris falling onto track [13,15,16,21]	De-vegetation programmes [21] Establishment of tree-free zones in rail corridor [4]	
	Excessive wind loading on structures such as masts and towers [3,16]	Strengthening of existing equipment, build in resilience to design of new equipment [32] Improved overhead wire tensioning systems [33]	
	Significant wave formation causing damage to the track [21]	Elevate infrastructure [11,21] Improved flood defences [21]	
	Increased risk of damage to bridges in high winds [3]	Use of guide vanes [34] Install damping devices [34,35]	
Lightning and electrical storms	Damage to buildings and structures from lightning strikes [3,10]	Install lightning conductors [29] Fitment of surge protection [22]	Vegetation management – specific species selection
	Forest fires caused by lightning [11]	Establishment of tree-free zones in rail corridor [4]	
	Damage to lineside trees from lightning strikes [3]		
High sea levels and storm surges	Coastal erosion of earthworks, structures and track [3,10,13,15,17,19]	Elevate infrastructure [11] Install rock armour [21]	Bioengineering and biotechnical stabilisation Dune and beach restoration Natural drainage solutions Reefs and mangroves Saltmarshes and coastal vegetation
	Seawater inundation of earthworks, structures and track [3,13,15,16,19–21]	Elevate infrastructure [11,21] Raise sea walls [27]	
	Damage to sea walls [3,10]	Flood defences designed for new floor event thresholds [21] Install rock armour [21] Raise sea walls [27]	

Sourced using the research protocol and findings presented in subsequent sections

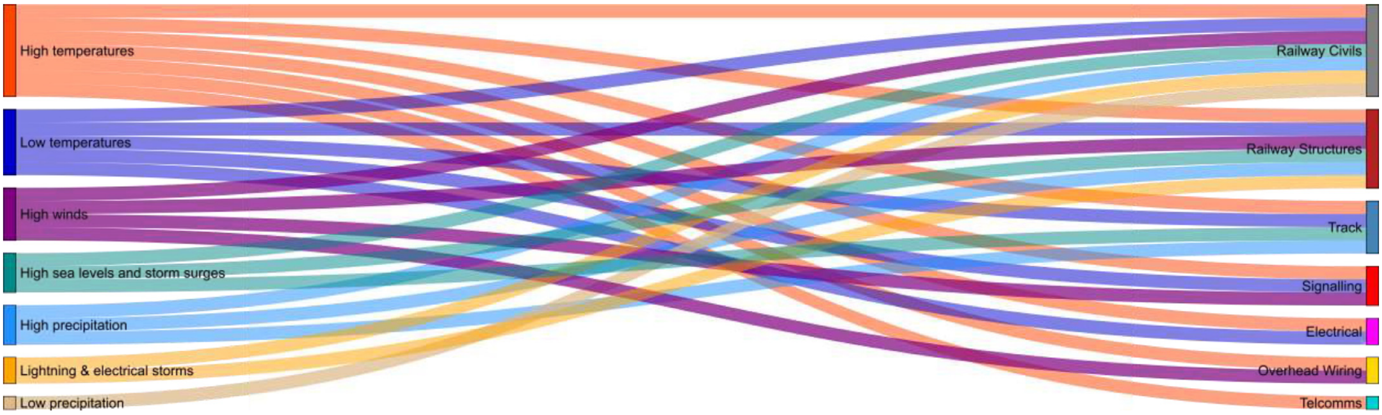

Fig. 1. Relationships between hydro-meteorological hazards and rail infrastructure categorised by engineering discipline.

2. Climate change adaptation options for rail

The Intergovernmental Panel on Climate Change defines adaptation as "the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities" [36:5]. Adaptation to climate change can incorporate a range of potential actions [37]. The prevailing approach across the world has involved a combination of direct, engineered (or 'grey') interventions such as sea walls and levees, and indirect (or 'soft') solutions [38] such as policies, planning and management approaches including early warning systems for extreme weather [11]. This review considers the physical, infrastructure-based adaptation options for railways.

Column C of Table 1 details the current engineered adaptation measures in use on rail infrastructure in response to climate-related impacts; data is sourced from a range of academic and grey literature (non-academic publications and reports), as at September 2021. Other than a small number of procedural changes to current practices (e.g. vegetation clearance and changes to rail installation techniques) the majority of measures in place are grey-engineered solutions. This is consistent with research by Stamos *et al* who, after clustering into categories suggested climate adaptation measures for transportation modes, including rail, found most of their options to be 'technical' [39]. They claim that this is "to be expected, as such solutions are often more straightforward in terms of implementation, compared to organizational or legislative measures, where potential bureaucracy may result in slow reaction times" [39:6-7]. This may not necessarily be systematically true however, as whilst some adaptation options are technically relatively easy to implement, the social and institutional complexity that their implementation brings about can prove much more difficult to address [40].

3. Nature-based solutions

Adaptation to climate change can include a variety of potential actions. Along with 'soft' and 'grey' interventions, there is widespread recognition that nature-based (or 'green') solutions can complement these approaches [38]. Nature-based Solutions (NbS) are defined by the International Union for Conservation of Nature (IUCN) as "actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" [41:4]. The ecosystem regulating services provided to society by NbS include the regulation of climate, water, erosion and natural hazards [41,42]. The United Nations (UN) recognize the contribution NbS provide to the 2030 Sustainable Development Goals (SDGs) through their support to these vital ecosystem services, and explain how NbS further underpin the SDGs by enabling access to fresh water, improved livelihoods, healthy diets and food security from sustainable food systems [43] whilst the IUCN advocates the powerful contribution that NbS can make in reducing the risks posed to society by climate change and natural hazards [41].

Although people have used the natural environment to cope with climatic variability for millennia [37], the NbS concept has gained increasing attention at national and international levels in the last decade or so because of the urgent need to find practicable, flexible, cost-effective CCA interventions that reduce vulnerability under rapid anthropogenic climate change [37,41] while improving sustainable livelihoods and protecting natural ecosystems and biodiversity (Mittermeier *et al*, 2008 in [41]). Examples include:

- Developing green infrastructure in urban environments (e.g., green walls, roof gardens, street trees, vegetated drainage basins) to improve air quality, support wastewater treatment, and reduce stormwater runoff and water pollution as well as improve the quality of life for residents; and,
- Using natural coastal infrastructure such as barrier islands, mangrove forests and oyster reefs to protect shorelines and communities from coastal flooding and reduce the impacts of sea-level rise [41].

NbS is broad in definition and scope [44]. It is considered as an umbrella concept that covers a range of ecosystem-based approaches, all of which address societal challenges [41]. Of the NbS categories and approaches proposed by Cohen-Shacham *et al* [41], three lend themselves particularly well to climate change impacts on railway infrastructure: Ecosystem-based adaptation (EbA), Green Infrastructure (GI) and Ecosystem-based disaster risk reduction (Eco-DRR), as explained below.

The Convention on Biological Diversity (CBD) defined EbA in 2009 as "the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people adapt to the adverse effects of climate change" [45:1]. EbA focuses primarily on CCA, with adaptation efforts leading to co-benefits that extend beyond adaptation [44]; for example, the rehabilitation of mangroves to protect coastlines [and their railways] from increased storms and floods whilst supporting biodiversity conservation [46]. EbA is generally deployed in the form of targeted management, conservation and restoration activities [37], which use ecosystem services purposively to increase human societies' resilience in the face of climate change [46].

Green Infrastructure (GI) is a "strategically planned network of natural and semi-natural areas with other environmental features designed to deliver a wide range of ecosystem services such as water purification, air quality, space for recreation and climate mitigation and adaptation" [47]. GI includes ecosystems that perform many of the same functions as conventional grey infrastructure, such as water collection, purification, storage, and conveyance (Dalton & Murti, 2013 in [41]). Compared to EbA, the connection between GI and CCA is less direct [44]; however, the infrastructure services are provided by ecosystems that deliver multiple other benefits, including climate adaptation. This could therefore present GI as a strong NbS candidate to be incorporated into, or potentially even replace, traditional mono-functional grey infrastructure [48] currently used in the rail environment. Whilst GI and the Natural Infrastructure (NI) approach are often used interchangeably [41,49] their application tends to refer to different contexts and scales. In particular, NI is used only at a landscape scale – a level which is likely to be beyond the physical and jurisdictional boundaries that rail infrastructure owners can influence. GI is therefore more directly relevant to railway-specific CCA interventions, however NI is not excluded from this research due to the complementary nature of the multiple ecosystem approaches which contribute to the NbS concept.

Ecosystem-based disaster risk reduction (Eco-DRR) may also have a role to play in terms of reducing risks to rail infrastructure from current and future climate-related hazards, for instance at locations prone to landslides, flood or storm surges. Eco-DRR is "the sustainable management, conservation, and restoration of ecosystems to reduce disaster risk, with the aim of achieving sustainable and resilient development" [50:4]. Although this definition does not include a reference to climate change, it is considered that Eco-DRR contribute to CCA as climate change is considered to be a risk amplifier now and, in the future [*ibid*]. Several initiatives are described interchangeably as either Eco-DRR or EbA, with Renaud *et al* slightly adapting the Eco-DRR definition to account for CCA, with Eco-DRR being "the sustainable management, conservation, and restoration of ecosystems to reduce risk and adapt to the consequences of climate change with the aim of achieving sustainable and resilient development" [50:4].

3.1. Green versus grey solutions

Although there are cases where hard, grey-engineered solutions for adaptation are necessary, there are many instances where nature-based approaches provide more cost-effective and longer-term solutions [51,52] (although no single NbS can solve all problems [53]). Many grey adaptation approaches are permanent and inflexible; this may be a key drawback in some settings [37,54]. For example, grey structures have been found to significantly alter the natural adaptive capacity of flood-prone areas, making both natural and social systems, such as railways, more vulnerable to flood hazards [55,56]. Meanwhile, most natural ecosystems are inherently adaptable; for example, subject to local conditions, coastal wetlands can migrate inland as sea levels rise [37].

A further advantage of NbS is that they can often be used in conjunction with other types of interventions, complementing and enhancing the effectiveness of grey infrastructure such as sea walls and dykes in a blended, cost-effective manner [37,41]. It is claimed that hybrid solutions, blending nature-based applications with engineered systems, may provide the optimal impact when considering environmental footprints, land requirements and cost expenditures [57], especially when their co-benefits are taken into consideration [53,58]. In this regard, the emphasis should be on NbS complementing rather than replacing grey solutions [59]. Multiple complementary NbS measures can be applied to one scenario to provide greater cumulative and spatial responses.

Bhattercharjee *et al* note that, whilst in the railway context, a well-connected and highly mobile population is likely to be in an advantageous position to better cope with flood-related hazards [55], the presence of transport infrastructure has been found to aggravate the degree of flood damage posing threat to human safety [60] due to the impermeability of typical construction materials triggering surface water flooding [61]. Given that physical infrastructure may exacerbate damages from natural hazards, its planning must be sensitive to local ecosystem dynamics [55]; NbS are therefore likely to better fulfill this need than grey adaptation options.

3.2. NbS potential in the rail context

Evidence suggests that with appropriate design and management, transport's 'soft estate' (the land owned by transport operators that is neither road nor railway [12]) and GI have the potential to not only deliver multiple ecosystem services which could benefit biodiversity and ecological connectivity, but also increase transport infrastructure's resilience to climate change [12]. For example, there is potential for vegetation in transport corridors to provide sustainable drainage to:

- Help manage surface water runoff and improve water quality;
- Improve air quality by capturing or acting as a barrier to the dispersal of pollutants produced by vehicles [12];
- Stabilize embankments; and,
- Provide resilience during heatwaves [10].

'Green track', a vegetative layer composed of turf or grasses between track beds, is in widespread use in light rail (tram) networks, found in almost all central European countries [62]. Differing track engineering and operational specifications (due to factors including weight of traffic, network accessibility, inspection and maintenance requirements [63]) mean that green track is not suitable for use on traditional 'heavy' rail. This review will not cover underground or light rail systems. Learning from the implementation of green track in light rail scenarios will however be applied when considering the use of NbS on conventional rail infrastructure.

The European Climate-ADAPT partnership confirm that the most advantageous adaptation measures are those that provide synergies with other measures leading to additional benefits and that NbS could therefore be used in adaptation of the rail system in a variety of ways (although they do not elaborate on these) [64]. However, at a time when railways are initiating sustainable land use programes which aim to protect ecosystems and create habitats for plants and animals on their networks [65], and include challenging 'no net loss' and 'net positive' biodiversity targets [66], the introduction of NbS could enable railways to simultaneously address both their CCA and biodiversity objectives. Acknowledging their potential to contribute to the UN SDGs, the uptake of NbS by the rail sector could facilitate industry-wide contribution to the Life on Land and Industries, Innovation and Infrastructure goals in particular [67]. This would enhance rail's reputation as a reliable and environmentally sound transport mode since the growth of rail transport, encouraging the shift from road to rail for both passengers and freight [29], would result in a reduction in greenhouse gas emissions (however, this potential can only be realised if railways are adapted to withstand impacts associated with climate change [68]). Wider ecosystem cultural service benefits could be derived through NbS providing enhanced scenic value to rail travellers, improving passengers' general well-being and with increased 'active travel' uptake delivering potential health benefits [69]. The natural screen provided by NbS could also present aesthetic and noise reduction benefits for those living near to railways.

Further, whilst the majority of literature presents a gloomy picture of the detrimental impacts of climate change, the European Commission showcase NbS as innovative solutions to contemporary societal challenges. With governments currently having great appetites for identifying cost-effective alternatives to grey or technological solutions, it is opportune timing for NbS to be considered as CCA options for the rail environment [52].

4. Knowledge gaps and research aims

Given that climate change affects all parts of railways in all parts of the world [29], it is vitally important to understand how transport infrastructure should be adapted to withstand the pressures of current climate conditions and predicted future change [70]. Due to the long asset lives of rail infrastructure, which is expected to operate for over 50 years, it is pertinent to integrate CCA into long-term railway planning, design, and management processes [68].

Whilst the number of articles concerning the impacts posed by climate change on transport infrastructure and operations may have grown rapidly in recent years [19], an initial search of academic literature revealed only limited coverage of CCA in the railway industry, highlighting the need for research in this area. In 2011 Eisenack *et al* found literature on adapting transport to climate change to be lacking [70]; this has more recently been confirmed to still be the case [17,20]. This scarcity of research is aligned with the wider general acknowledgement that there is insufficient literature investigating climate threats within the rail sector [16]; where it is considered, the major focus is generally on climate change mitigation, with countries only recently starting to build capacities for adaptation [71].

Wang *et al* [16,20] found climate-related studies on transport infrastructure to focus on short-term climate threats, and in transport sectors such as ports and road but not yet in the rail sector, as confirmed elsewhere [11,70]. A climate risk assessment survey of UK rail stakeholders found that only one-third of participants had implemented a climate adaptation plan and less than half of those participants who had not yet developed one acknowledged they would consider developing one in future [16]. Furthermore, Eisenack *et al*'s review of observed and proposed adaptation measures in the transport sector found that, despite rail being an important mode of transportation, merely 9% of all adaptations fell into this category [70].

Recognizing that research is still at an early stage, Wang *et al* claim there is “a vacuum to be bridged” in the gap between existing literature on adaptation measures for rail which is either too vague or overly detailed, and research that fails to address the factors that constrict or could promote the implementation of adaptation measures [20:12]. Where literature does address rail CCA, Armstrong *et al* identify a gap between the acknowledgement of the need for adaptation and details of the required interventions [17].

Whilst Wang *et al* recommend that ‘country-specific’ evaluations of rail resilience to climate change are urgently needed [16], it could be more pragmatic to investigate impacts on rail infrastructure on a climate basis as opposed to location. Physical rail network risks will not be evenly distributed across nations, e.g. due to geographical and climate change patterns [60]. It is recognized that the occurrence and severity of HMH are specific to regional variation [72] and that the climate challenges railways face in future are already being managed somewhere in the world today [29]. Quinn *et al* therefore recommend that the rail sector draws upon international analogues, where a region may increase its preparedness for projected climate changes by learning from the existing experience of the same conditions in another region [*ibid*]. For example, the regions with both climate and railway analogues to Great Britain (GB) are France, the Netherlands, Belgium, Germany and Denmark. The GB rail industry has undertaken focused stakeholder engagement on railway networks' weather resilience and CCA activities with representatives from most of these countries railways [73]. Engineers Canada highlight the importance of coordination across jurisdictional boundaries to advance adaptation solutions and increase the resilience of the transport sector [11].

A further (social) geographic observation is that literature concerning transport sector CCA options focus mainly on the Global North [20,74,75], when it is the Global South that may be more vulnerable to climate change. The Global South is more likely to suffer from less adequate infrastructure which would be less able to accommodate adaptation measures that may need to be introduced [75], whilst also having fewer financial resources available to fund such measures. Infrastructure networks are generally not as developed as in the Global North, meaning there is a greater emphasis on expansion [75,76]; this may present an opportunity as it is likely to be easier and more cost effective (subject to sufficient funds and institutional capacity) to embed climate change considerations into the planning, design and construction of new infrastructure [58,75] than retrofit existing assets. Given the potential relative cost-effectiveness of NbS, research into their application in the rail context may present CCA options to the Global South which are significantly more economical, thus enabling the implementation of adaptation measures that may not otherwise be possible.

The general absence of academic literature on CCA in the rail context could be explained by Great Britain's rail infrastructure owner, Network Rail, taking the decision to move from “subjective and expert review-based knowledge” of weather and climate change risks to “more detailed internal analysis” of asset failure and weather data [3], i.e. shifting from academic to grey literature. Similarly, most of the practical adaptation proposals found by Armstrong *et al* were found to be in grey literature [17] reflecting the fact that grey literature is more accessible to, and likely to be generated by actors with a frontline role in infrastructure planning, design, construction and maintenance. With regard to NbS, there has been significant research conducted on its application to respond to the impacts of climate change in cities and urban areas [77]; however, literature on its use on railways is scarce.

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

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

5. Methodology

5.1. Review framework

A literature review protocol was established to respond to the question “what is the evidence base on the use of NbS being implemented as CCA measures in the railway context?”. Using the “PICO” approach outlined by Pullin *et al* [78] the following population, intervention, comparator and outcome elements were used to frame the review question:

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

5.2. Search protocol

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

The search terms for the three categories were linked using the Boolean operator “AND”, while the Boolean operator “OR” was used to include the keywords within each search category. A complete list of the search categories and keywords used are included in Table 2. See Supplementary text S1 for the full search term sequences applied.

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

A review of the sole article found in this search [79] revealed that the inclusion of “railway” in the abstract relates to the research being

Table 2
Literature review search terms applied.

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

conducted on a park located on a former railway site i.e. not in an operational railway setting. This paper is therefore not relevant to the scope of this research and the outcome confirms the paucity of knowledge on this topic.

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

5.3. *Initial findings*

Findings are presented in Table 3; these are recorded based on the type of literature in which the NbS examples were found. Where rail-specific examples were located, they are captured either in the 'Live rail example' column or highlighted (in red text) in the column corresponding to the literature type in which the evidence was found. As shown in Fig. 2, this approach may help to establish the level of confidence in the validity of each proposed NbS, with a higher level of evidence inferring a more robust solution. Additionally, the more times an NbS has been found in literature (reflected by multiple references), the greater the inferred level of agreement over that NbS and subsequently higher the confidence level over its potential suitability (approach taken from [80,81]).

6. Results and discussion

Five examples of the application of NbS in live rail environments were found: four in grey literature promoting best practice, and currently implemented in Australia and London, one mentioned in a journal article. The paper featuring the latter example focusses on carbon sequestration and sink, and the air pollution reduction potentials of a green railway corridor in Sydney, with Blair *et al* describing the lineside vegetated and open space areas as "fine examples of green infrastructure" [82:1717]. They explain how, with an appropriate selection of vegetation species, the corridors can be used to offset carbon emissions from railway operations whilst simultaneously improving air quality, reducing pollution, delivering biodiversity gains, and improving urban design and property values. Last but not least, they can ameliorate storm water flows [*ibid*]. Because the article does not explicitly mention CCA however, it did not feature in the original search results. As Sarabi *et al* point out, since NbS is a relatively new concept, it is not clearly defined and thus there is a lack of understanding what NbS are and are not [83]; this means there may be many further examples of NbS in use in rail, providing CCA services, without being recognized or labeled as such, and therefore not locatable. The launch of a Global Standard for NbS by the IUCN [84] along with principles for their implementation and upscaling [85] will support increased awareness of NbS and interest in their use.

All five examples regard NbS CCA measures in response to high precipitation, causing flooding or a resultant increased risk of erosion and landslides requiring greater geotechnical controls. This aligns with just over half of the NbS examples being found in this research concerning CCA options for high precipitation hazards (see Fig. 3).

Whilst high precipitation may not impact as many rail infrastructure assets as other HMH i.e. compared with high or low temperatures, or high winds (Fig. 1), the frequency and/or magnitude of high precipitation events and their resultant impacts on infrastructure may have prompted a greater amount of research into NbS as CCA options for this hazard. This could also explain why the only live rail examples that were identified address this particular HMH and it is perhaps no coincidence that flood events had the largest cost impact of all weather-related events suffered in GB between 2006-2016, with costs estimated to be circa £150 million [84].

Despite not being fully examined in peer-reviewed academic literature, the five live rail examples found in this research are categorised at the top of the level of evidence hierarchy proposed in Fig. 2 due to them currently being implemented and highlighted as industry best practice. Whilst there is a clear research gap to be addressed to prove their successful implementation, showcasing examples found directly within the rail sector strengthens the case for and provides an excellent basis on which to expand NbS research in the rail sector, providing potential case studies if/when their effectiveness has been demonstrated. The lack of scientific evidence documenting these practices – and *vice versa*, the failure for grey literature to reflect academic literature on climate change adaptation and/or the potential viability of using NbS - may reflect a lag between academic research in this area and an industrial drive to implement reactive operational responses to current extreme weather events (as before, the majority of these potentially being high precipitation events) rather than intentional, longer term climate change adaptation measures. This resonates with the findings of Lindgren *et al* whose study on climate change adaptation on Swedish railways noted the implementation of non-deliberate adaptation measures in response to present day climate-related events and recommended the adoption of anticipatory, proactive and planned adaptation strategies for future climate change [4]. Climate change is extremely complex. Few railway organizations have in-house expertise on this topic, similarly, meteorologists are not railway experts [29]. Multidisciplinary collaboration between climate and environmental scientists with rail industry professionals could therefore enable the sharing of expert knowledge to support the development of CCA measures relevant to rail, including NbS.

Findings from this research have been incorporated into Table 1, Column D to present potential NbS options as alternatives and/or to complement grey engineered CCA options for rail infrastructure, per HMH. Fig. 4. illustrates the NbS found to be most appropriate for each rail engineering discipline, extending Fig. 1 to align the interrelationships between HMH, rail infrastructure (by engineering discipline) and relevant NbS. Fig. 4. can be referred to alongside Table 1 to aid the con-

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

Hydro-meteorological hazard	Live rail example	Case study	Field test	Review	Concept
High temperatures		Use of green corridors to provide cooling [94,95]	Use of plants and mosses to control soil temperature preventing [96]	• Green corridor to provide cooling [12,97] • Vegetation selection to reduce fire risk [4]	Use vegetation for shading and cooling [68,98] • Selection of suitable vegetation for near the rail corridor [68] • Use of plants with relatively high moisture content and low levels of volatile oils [69] • Practice the controlled removal of vegetation to prevent wildfires [52,99]
Low temperatures	• Green walls to prevent rockfall [69]			• Forests to stabilize snow reducing the risk of avalanches [64] • Vegetation management to prevent snow loaded trees and branches falling onto tracks [93] • Vegetation strategies to ensure the stability of earthworks and soil structure [93] • Forests to protect against rockfall [64]	• Thermogenic plants
High precipitation	• Vegetation strategies to reduce risks from flooding [69,82,87] • Green infrastructure for embankment stabilisation [69]	• Wetlands construction, restoration and conservation [49,52,74,94,100] • Establish flood bypasses [49] • Riparian buffers [49,94] • Bioswales, detention ponds, infiltration basins, living fascines, planted embankment mats [94] • Reconnecting rivers to floodplains [49] • Re/afforestation and forest conservation [49] • Restoration of ponds and lakes, renaturing rivers and streams, Sustainable Urban Drainage Systems [95] • Introduction of grassland to alleviate runoff and flooding [74,101] • Vegetation used as watershed management [74,102] • Introduction of grassland to alleviate erosion [101] • Restoration of degraded vegetation [103] • Natural revegetation as soil erosion control [104–106]	• Japanese Millet monoculture or dominated seed mixture for soil erosion control [107] • Forest management to reduce stream flows [108,109] • Use of moss and lichens for erosion control [110] • Use of nature-based erosion barriers for rangeland [111] • Stable enduring species as erosion control [112] • Use of grasses to rehabilitate Badlands, facilitating soil erosion control [113] • Parallel contour seeding as run-off control [Badia *et al* in [74] • Use of seeded perennial grasses for erosion control [114] • Natural revegetation [115] • Artificial sparsely forested grassland restoration for erosion control of sandy grasslands [116] • Retention of mature forest as soil erosion control [117] • Avoid use of non-native herbs when revegetating [118] • Natural fallow as soil erosion control [18] • Use of shrubs and deep-rooted grass for slope stability [119] • collective tree, shrub & herb assemblages for erosion control and landslide prevention [120]	• Vegetation cover and root structures to protect again soil erosion [12,64] • Ponds, wetlands, strips, hedges, shelterbelts, bunds & riparian buffer [97,121] • Sustainable drainage systems, bioretention swales and basins [64,121] • Forests to reduce flood risk [64] • Peatlands and grasslands to store water [64] • Soil bioengineering, cultivation or restoration of slopes, live fascines, vegetating crib walls, optimise management of forests, rivers and streams [121] • Biotechnical stabilisation to enhance grey engineered structures [31] • Mulch blankets, hydro-seeded grass cover and deeply rooted woody vegetation [31]	• Vegetation strategies to ensure the stability of earthworks and soil structure [93] • Vegetation strategies to reduce risks from flooding [93] • Use plantings for erosion control [98] • Use wetland and other natural infrastructure to help control flooding [98,122] • Small watercourses are better than man-made drainage [4] • Retain forest cover on steep slopes [52,99] • Encourage re-vegetation of riverbanks [52,99] • Use balancing ponds to contain surges and release slowly [122] • Plant trees, hedges and/or perennial grass strips to intercept surface run-off [122] • Allow for natural erosion processes rather than try to prevent them [52,99]

(*continued on next page*)

Table 3 (*continued*)

Hydro-meteorological hazard	Live rail example	Case study	Field test	Review	Concept
Low precipitation		• Restoration of ponds and lakes, renaturing rivers and streams [95]		• Soil conservation and connectivity of the landscape (increase infiltration or reduce surface run-off) to restrict droughts [121] • Maintain vegetation cover in dryland areas [64] • Lakes & wetlands, blue-green infrastructure [97]	• Vegetation strategies to ensure the stability of soil structure [93] • Maintain and enhance natural wetlands [99]
High winds			• Strip cutting of coastal forests to prevent wind damage [123]	• Shelterbelts [12,64] • Greenbelts, and other types of living fences to provide wind barriers [64] • Seagrass beds, coral reefs, oyster reefs, salt marshes [124] • Use of natural coastal ecosystems to reduce wave heights [74]	• Planting of trees able to withstand higher winds [68] • Tree selection to withstand higher wind [4] • Vegetation strategies to reduce risks from high winds and leaf fall [93] • Vegetation strategies to ensure the stability of earthworks and soil structure [93] • Planting of evergreen trees
High sea levels and storm surges		• Dune restoration and beach regeneration, salt marsh and coastal wetland regeneration, creation of oyster reefs [95] • Protecting/ restoring reefs (coral/oyster) [49] • Protecting/ restoring mangroves, coastal marshes and dunes [49] • Dune restoration and beach regeneration [125] • Use of marshes [126]	• Emergent plants to attenuate waves [127] • Vegetation of dunes to reduce coastal erosion [128,129] • Creation of oyster shell reefs to reduce coastal erosion [130,131] • Restoration of sand banks, beaches & dunes [132]	• Coastal vegetation, wetlands & coral reefs [64,121,124] • Seagrass beds & saltmarshes [64,124] • Mangroves [64] • Construct artificial dunes, planting on natural dunes [121,124] • Use of natural coastal ecosystems to reduce wave heights [74] • Seagrass beds, Coral reefs, vegetation and wetlands [64,121]	• Dune restoration and beach regeneration [99] • Create, restore and/or enhance shellfish & coral reef growth [99] • Protecting/restoring mangroves, coastal marshes and dunes [99] • Create new, restore and/or protect intertidal muds, saltmarshes & mangrove communities, seagrass beds & vegetated dunes from degradation or loss [99] • Seagrass beds, Coral reefs, vegetation and wetlands [99]

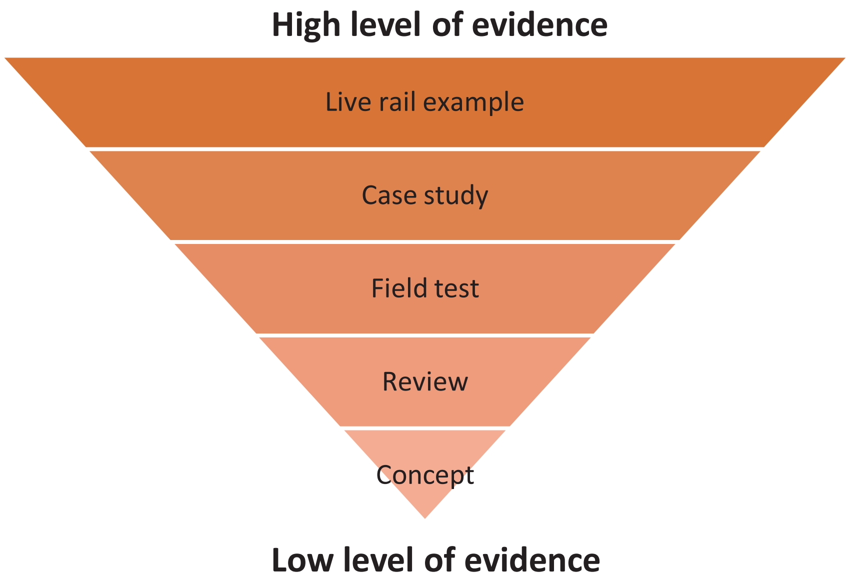

Fig. 2. Level of evidence based on literature type used to inform potentially suitable Nature-based Solutions.

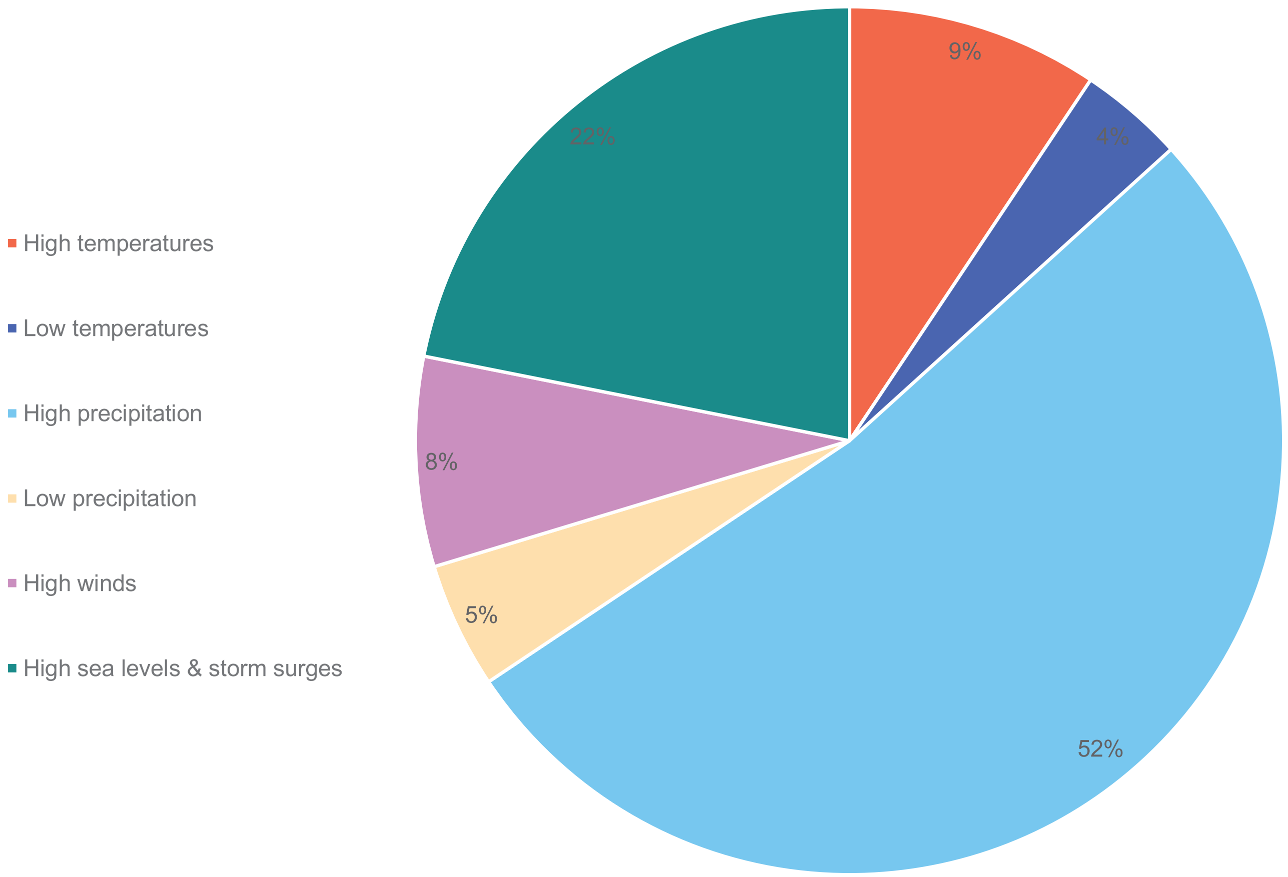

Fig. 3. Proportion of nature-based solutions potentially suitable as climate change adaption measures for rail found in literature, per hydro-meteorological hazard.

sideration of NbS as rail CCA measures and may also be used to help prioritise research efforts on this topic. For example, Figs. 1 and 4 show that the Railway Civils and Railway Structures engineering disciplines host the infrastructure impacted by the greatest number of HMHs, suggesting that these disciplines may be priorities on which to initially focus CCA efforts. Further, as each rail discipline typically has its own suite of design, operation and maintenance standards and associated guidance, displaying the NbS relevant to each rail discipline could aid the development of targeted NbS resources, tailored to each discipline and their respective audiences.

When viewing Fig. 4 in the context of how each category of NbS may provide CCA services to multiple rail infrastructure assets (by engineering discipline) it reveals that vegetation shading and green corridors are likely to provide CCA solutions which benefit the widest range of rail infrastructure. Further, Fig. 4 helps to show how the use of multiple NbS at one location may simultaneously address several HMH across multi-

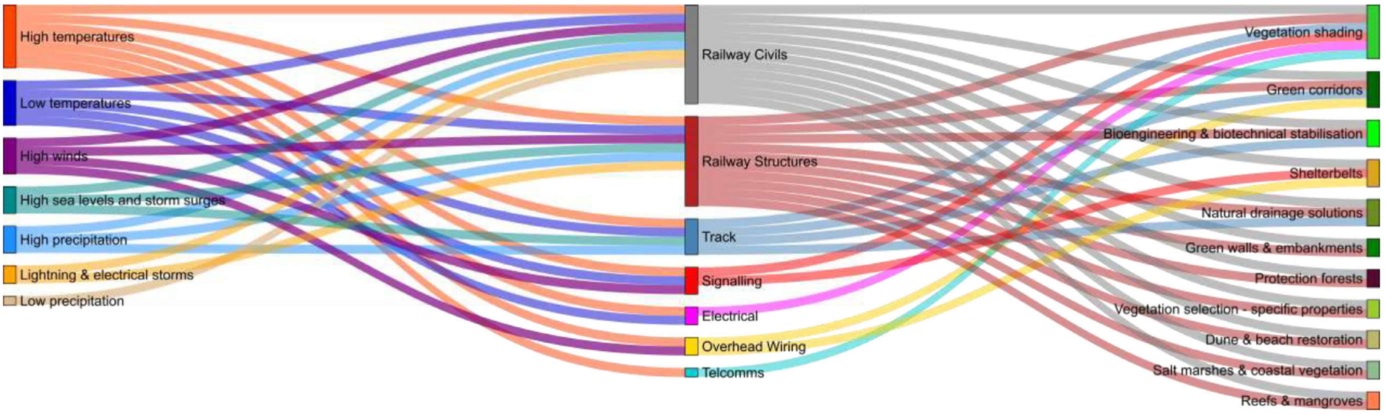

Fig. 4. Relationships between hydro-meteorological hazards, rail infrastructure (by engineering discipline) and potentially suitable Nature-based solutions.

ple rail infrastructure assets; this may result in a greater cumulative CCA response and the diagram may be used to inform research into finding the most effective combination(s) of NbS in this regard.

Globally, government agencies, communities and other organizations are recognizing the importance of 'greening' grey infrastructure and examples of railway corridors being revegetated are beginning to appear [82]. Whilst limited documented examples of the application of NbS in the rail CCA context were found in the literature review, representing an obvious opportunity for future research, both an appetite and recommendations for research on this topic were confirmed in the literature, as discussed below.

In London, UK, as part of the Thameslink Programme's Net Positive Biodiversity Policy, works on the Bermondsey Dive Under involved the construction of embankments on either side of the railway on which wildflowers were planted, creating corridors and ecological 'stepping-stones' to the wider area. A native species wildflower mix was chosen with low maintenance requirements and attractiveness to pollinators; the project described the wider NbS benefits of this feature as including reduced run-off, and an increased quality and quantity of green and blue infrastructures [85].

The Australian Adelaide – Seaford rail line provides another example of corridor greening, although much of the work involved replacing trees and shrubs which had to be removed as part of the electrification of the line. The project also aimed to create a biodiversity corridor in which flora and fauna can thrive [86]; however, the study did not acknowledge (or at least document) the bonus CCA ecosystem services the vegetation would deliver.

Transport for New South Wales (TfNSW), Australia, have developed a guidance document "Integrating Green Infrastructure" which (in the only example of its kind found in research to date) promotes opportunities to integrate GI during the planning and design of transport assets, including rail corridors [69]. Noting the importance of the ecological services GI provides to the public, customers, neighbors, as well as their own organization, TfNSW declare it is "crucial" for GI to form part of planning and design thinking from the outset of a transport infrastructure project [*ibid*:7]. They provide guidance on how GI may be incorporated into the TfNSW network and their organizations project planning process, along with live rail examples of vegetation planting to stabilize embankments, the use of native ground cover to manage flood risk and a green wall rockfall barrier.

A further proposed example of the use of vegetation as a CCA NbS is by Network Rail in the UK who, in partnership with the Environment Agency and Leeds City Council, will be planting up to two million trees to reduce stream flow in the upper catchment of the River Aire as part of a strong focus on using "Natural Flood Management" to reduce flood risk at a location which suffers from repeated flooding [88].

Blair *et al* reference woodland planting undertaken along two and half kilometres of railway corridor and adjacent lands in London, UK [82]. The key objective of this project was aesthetic, providing enhanced views for the local community and improving the travelling experience for rail users, whilst also protecting wildlife habitats. The project failed to consider the CCA benefits this undertaking will have delivered (National Urban Forestry Unit, 2012 in [82]), meaning a lost opportunity in support of the body of evidence for this ecosystem service. It should be noted that linear vegetation corridors such as railways do not only have positive effects; they may also facilitate the spread of invasive species [89,90] and attract pests [91].

The promisingly titled "Adaptation of Melbourne's Metropolitan Rail Network in Response to Climate Change" study [92] considers a range of adaptation responses, including infrastructural and non-infrastructural options. Each of the infrastructure adaptation strategies focused on grey engineering solutions. The only potential inclusion of NbS is proposed in the recommendation to shade signaling equipment, although the report does not explicitly state or suggest that this will be via the provision of vegetation cover. Great Britain's Rail Safety and Standards Board (RSSB) does recommend this use of vegetation to provide shading for lineside equipment. They also promote targeted planting of vegetation around track at risk of overheating to reduce air and surface temperatures of track, highlighting that these options may also have benefits for local drainage issues [10]. In a further report, the RSSB recommend that research be conducted into options for long-term vegetation strategies to ensure the stability of earthworks and soil structure, and to reduce risks from high winds, leaf fall and flooding of all types given projected climate change; suggesting this be considered as taking a GI approach to the design and operation of the Great British railway [93].

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

7. Conclusion

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

Declaration of Competing Interests

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.

CRediT authorship contribution statement

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

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Supplementary materials

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