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Planning for fauna-sensitive road design: A review

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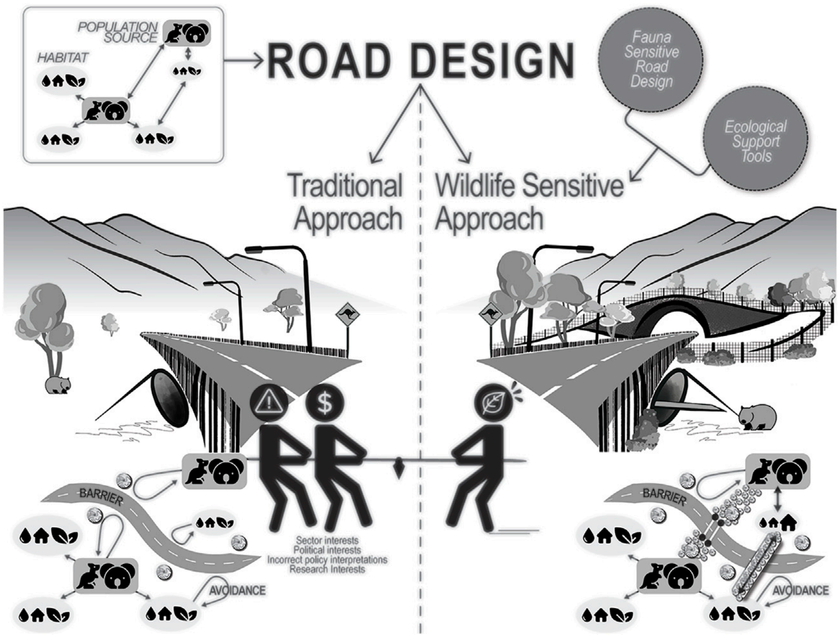
Roads can have significant negative impacts on wildlife. *Fauna-sensitive road design* (FSRD) can alleviate adverse impacts on several species by installing specialised structures, such as wildlife crossing structures. This developing subfield has generally, however, had a limited impact on transportation planning and management. Indeed, most research is focused narrowly on technological solutions, instead of broader policy learnings. This systematic quantitative literature review (SQLR) of international literature sought to identify the biodiversity concerns acknowledged in transport planning policy, as well as the barriers to the adoption of environmental policies within transport planning. Despite considerable literature available on the impacts of roads on wildlife elsewhere, acknowledgement and consideration of both fauna movement and fauna-sensitive road design were limited in road transportation planning research. More broadly, failure to achieve environmental objectives within transport planning occurred primarily as a result of competing sector interests (conflicted knowledge), different political objectives (political interest), and incorrect interpretation of policies. In essence, the results add new layers of understanding to the field of transportation planning and policy, in particular, the gaps in acknowledgement of wildlife movements and the limitations of current fauna-sensitive road design considered. Importantly, the review identified multiple ecological support tools available to transport policy- and decision-makers. Integration of these in road transportation projects could facilitate enhanced uptake and adoption of FSRD measures and thus foster improved sustainability of the transport network.

KEYWORDS
fauna sensitive road design, environmental impact assessment, linear transport infrastructure, road ecology, transport planning, sustainable transport network

Introduction

Road ecology is a recent sub-field that sits at the intersection of environmental science and engineering. Much of this research is, however, focused on greenhouse gas emissions and pollution (Li et al., 2014; Pang et al., 2021), technological innovations (Cai et al., 2022; Yu and Wan, 2022), and broad ecological impacts (Liu et al., 2010). Few studies have examined the broader impacts of transportation infrastructure planning and design on wildlife and targeted mitigation measures for these. *Fauna-sensitive road design* (FSRD) is



GRAPHICAL ABSTRACT

a tool for transport policy that acknowledges the negative impacts of roads on wildlife and seeks ways, through modifications to road design, that facilitate the safe and natural movement of wildlife across roads (Iuell et al., 2003; van der Ree et al., 2015b). Although costly, such modifications are highly successful in mitigating the road impacts on wildlife (Iuell et al., 2003; van der Ree et al., 2015a). Ecological research in general, however, has had very little impact on transportation planning and management, in part due to the demand for transport practitioners to achieve political and community values (Bond et al., 2014; Marsden and Reardon, 2017; Akgün et al., 2019). This has culminated in an applied field of research narrowly focused on technological solutions (Geerlings and Stead, 2003; Akgün et al., 2019).

This paper provides a systematic quantitative literature review (SQLR), using the De Vos and El-Geneidy (2022) review framework, of international transport literature on LTI environmental and defragmentation policy. This is a well-used technique in several fields to review such material in a robust manner but does have some limitations, including potential bias of keyword search terms and database selection. The review will be used to synthesise and articulate the current state of research within the field of transport planning, providing useful insights for transport practitioners, as well as new avenues for future research. This will be guided by the three questions: A) what environmental concerns are presently considered in transportation infrastructure planning? B) what conditions have facilitated or impeded environmental policy transfer and uptake?, and; C) what planning tools are available that would assist transport planners and decision-makers to achieve improved project outcomes, in particular FSRD? In essence, the results will add new layers of understanding to the field of transportation planning and policy, in particular, the gaps in acknowledgement of wildlife movements and the limitations of current fauna-sensitive road design considered. Additionally, the review will also bring to attention several ecological support tools to aid transport policy- and decision-makers in designing and planning sustainable road projects.

Literature review

Linear Transport Infrastructures (LTIs) (highways, paved roads, unsealed roads, and railways) are an important aspect of the transport network, enabling the movement of people and the safe distribution of services and products. These infrastructures fragment and degrade landscapes and disrupt natural habitats over considerable distances, an outcome known as the *road effect zone* (Forman and Deblinger, 2000; van der Ree et al., 2015b). This can have significant negative consequences for wildlife within affected landscapes (Pell and Jones, 2015; Johnson et al., 2017; Johnson et al., 2022; Papp et al., 2022). Habitat fragmentation and degradation are recognised as the greatest threats to species survival worldwide (Benítez-López et al., 2010; Papp et al., 2022). LTI must incorporate solutions that address this if the *sustainable development goals* (SDGs), especially

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9.4 and 11.6, are to achieve the 2030 agenda for sustainable development (United Nations, 2015).

Within the *European Union* (EU), member states have a legal requirement to address habitat fragmentation caused by LTI under the EU TEN-T Regulations, 2013. The EU Member States are committed to the restoration of ecological networks through the enactment of 'defragmentation' programmes and policies for existing and future transport networks (Trocmé, 2005; van der Grift, 2005; Jaeger et al., 2011). Belgium, Czech Republic, Denmark, France, Hungary, Netherlands, Norway, Spain, Sweden, Switzerland and the United Kingdom all developed National State-of-the-Art Reports on Habitat Fragmentation due to LTI (Damarad and Bekker, 2003). The reports were informed by best management practices designed to assist transport planners with the integration of environmental aspects throughout projects (Damarad and Bekker, 2003; van der Ree et al., 2015b).

These nation-specific policies, however, do not necessarily reflect those at the supra-national level. Several authors regard the transposition of supranational (EU) level legislation and policy to have been highly heterogeneous, made difficult by the multitude of national and administrative systems that occur between each of the fifteen Member States (Ledoux et al., 2000; Diaz, 2001; Morris, 2011; Papp et al., 2022). Continued urban sprawl and grey infrastructure development, including transport infrastructure, contributed significantly to the EU's ambitious, yet failed attempt to halt biodiversity loss by 2020 (EHF, 2019). This resulted mainly from a lack of political will (EHF, 2019). Outside the EU, there is even less consistency in policy approaches towards habitat fragmentation from LTIs. A greater understanding of the FSRD science-policy interface is therefore required to better understand its overall influence on the design and construction of road transportation infrastructure.

Methodology

A *Systematic Quantitative Literature Review* (SQLR) was performed using the Pickering and Byrne model (2014) and PRISMA-P guideline (Moher et al. 2009). This was further modified to incorporate the De Vos and El-Geneidy (2022) review framework to ensure new contributions to the transport field are clearly articulated. This needs to be by way of: A) a conceptual model; B) future research needs; and or, C) policy implications. The present study will address the latter two: future research needs and policy implications.

An exhaustive search of international scholarly literature was carried out between 2020 and 2021 and focussed primarily on the collation of articles in the period post-Earth Summit (1992–2020). The 1992 *Convention on Biological Diversity* set legally binding goals for sustainable development (SD), including provisions for a sustainable transport network. This makes 1992 a useful start date for a scholarly review. English-

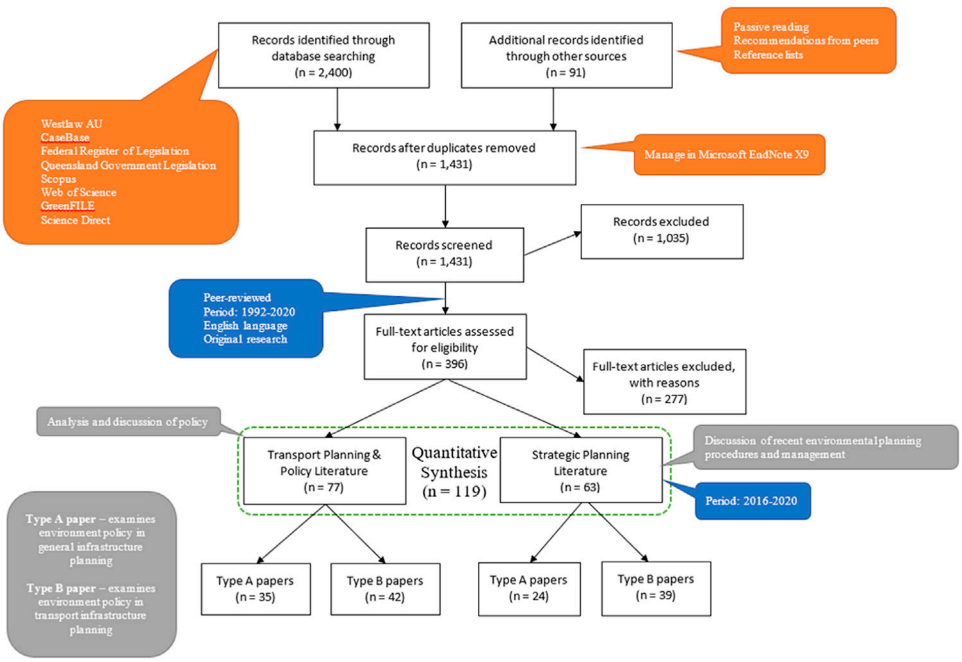

FIGURE 1
Preferred reporting items for systematic review and meta-analysis (Prisma-P) flow-chart.

language, peer-reviewed research articles were obtained through a search of eight journal databases (see Figure 1). Peer-reviewed literature was selected as the primary focus of this investigation to enable the concentration of only scientific knowledge, and thus ensure scientific rigour. Grey literature was intentionally excluded. Due to the inherent nature of many peer-reviewed scientific texts, it was broadly assumed these would (indirectly) capture and build upon the body of other non-scientific texts (reports, statues, books, etc.), including those published in different languages. A complete list of keyword strings used in database searches may be found in the Supplementary Material.

Results

A cumulative total of 2,400 search results were obtained from 143 individual search attempts, with an additional 91 articles identified through other sources (i.e., passive-reading, contributions from supervisors, peers and professionals, article reference lists, etc.). A total of 119 articles were retained for quantitative analysis; 21 papers were assigned to both "Transport Planning and Policy Literature" and "Strategic Planning Literature" categories (Figure 1).

Transport planning and policy literature

A total of 77 articles were reviewed under the 'Transport Planning and Policy' category. Thirty-five (35) 'Type A' papers and forty-two (42) 'Type B' papers were identified.

In terms of spatial scale, strong geographic bias was observed within the broader dataset of published literature (Type A and B): most papers examined Europe (73.7%), followed by Australia and North America (6.6% respectively). Approximately 13.2% of studies were general in their examination (i.e., not region-specific). Stronger geographic bias was observed when only Type B papers were considered: 88: Europe (88.1%), North America (4.8%), and none in Australia. Approximately 7.1% of studies were general in their examination.

In terms of methodological approach, most papers (91.9%) in the broader dataset used a combination of *literature review* (n = 43; 59.8%), *case study* (n = 34; 44.2%) and/or *document analysis* (n = 24; 31.2%) methodologies. In comparison, <50% of published literature used a combination of *interviews* (n = 16; 20.8%), *observation* (n = 14; 18.2%), and *modelling* (n = 10; 13%) methodologies. Very similar trends were observed when only Type B papers were considered.

How environmental concerns are acknowledged and framed within the literature indicates practitioners and decision-makers current level of understanding of environmental concepts. Within the broader dataset of papers, articles tended to frame environmental concerns in terms of *environment* (broadly) (n = 44; 57.1%), *biodiversity* (n = 25; 32.5%) and *protected area/corridor* (n = 23; 29.9%). Few papers raised concerns over fauna movement (n = 11; 14.3%). However, when only Type B papers were considered, environmental concerns were framed in terms of *environment* (broadly) (n = 26; 61.9%), *pollution/contamination* (n = 15; 35.7%), and *biodiversity* (n = 15; 35.7%). Acknowledgment of fauna movement was similarly low (n = 9; 21.4%).

It is also important to understand how and why environmental policy resistance occurs in transportation planning. Within the broader dataset of papers, policy resistance typically resulted from *conflicted knowledge* (n = 56; 72.7%), *political interest* (n = 48; 62.3%), *procedural focus* (n = 37; 48.1%), *interpretation* (n = 36; 46.7%), and *statutory recognition* (n = 34; 44.2%). A similar trend was evident when only Type B papers were considered. Although, *conflicted knowledge* (n = 31; 73.8%) and *political interest* (n = 26; 61.9%) featured more prominently.

Strategic planning literature

In addition to our understanding of the current knowledge and practice, it is also crucial to explore the range of recommendations proposed by researchers to improve these; this will provide some indication as to the anticipated direction of future research. Of the final paper dataset (n = 119), some 63 papers referred to strategic planning of infrastructure projects: twenty-four (24) Type-A papers and thirty-nine (39) Type B papers. Two (2) papers were assigned to both Type-A and Type-B categories.

In terms of spatial scale, published literature within the broader dataset displayed strong geographic bias: 71.4% of studies were performed in Europe (n = 45), and 3.2% each in Australia and North America (n = 2). Approximately 20.6% (n = 13) were not region-specific. Similar geographic bias was observed when only Type B papers were considered.

In terms of methodological approach, most published literature within the broader dataset tended to rely on three approaches: *literature review* (n = 58; 92.2%), *case study* (n = 37; 58.7%), and/or *modelling* (n = 35; 55.6%). Other experimental methods were less frequently used: *interviews* (n = 11; 17.5%), *document analysis* (n = 8; 12.7%), and/or *observation* (n = 4; 6.4%). Very similar trends were observed when only Type B papers were considered.

Most published literature within the broader dataset tended to frame environmental concerns in terms of *protected area/corridor* (n = 37; 58.7%), *fragmentation* (n = 36; 57.1%), and *fauna movement* (n = 25; 39.7%). A similar trend was evident when only Type B papers were considered.

It is also important to understand where future research effort is being directed in transportation planning. Published literature in the broader dataset generally recommended further research into *strategic assessment* (n = 49; 77.8%), *GIS/modelling* (n = 28; 44.4%), *data management* (n = 23; 36.5%), and *stakeholder engagement/collaboration* (n = 22; 34.9%) as means to improve current practice. A similar trend was evident when only Type B papers were considered. However, *strategic assessment* (n = 34; 87.2%) featured more prominently.

This analysis has elucidated the main foci and biases of the literature reviewed. A comprehensive synthesis of this literature is reported and discussed in the following section.

Discussion

The large body of literature reviewed in this paper indicates substantial gaps within the fields of transport planning and transport policy that warrant further investigation. The potential findings within these areas may have a considerable bearing not only on the design and management of road corridors but also on land management practices more broadly. The results of the SQLR are discussed in relation to each of the three key research questions to create a systematic and organised overview of the topic.

Dissemination of road ecology principles in transport planning

There is a significant body of research into the environmental aspects of transport planning and policy. Research effort within this field was most heavily focused on European countries (see Damarad and Bekker, 2003; Trocmé 2005; Pettersson 2013; Emberger 2017; Sobolewska–Mikulska, 2019; Papp et al., 2022). This may be attributed to two key interrelated factors. The first is the relatively long history of human colonisation, subsequent land development, and a resultant documented decline in biodiversity within this region (Diaz 2001; Mallard and François, 2013; Zisenis 2017). The second is the considerable pressure on the Member States to achieve their obligations under supra-national and international law (Damarad and Bekker, 2003; Lammerant et al., 2014; Papp et al., 2022); indeed to "lead by example", be "innovative", and "pioneer" environmental policies (EHF, 2019). The same pressures are not as apparent in North America or Australasia.

Environmental aspects that received the most attention included "environment" (in general terms), "biodiversity", and 'pollution/contamination'. However, of the papers in the "Transport Planning and Policy" category (n = 41), relatively few identified "fauna movement" (n = 7). In comparison, some 63 papers referred to strategic planning in some way. Of these, 39 explicitly discussed strategic planning within transport infrastructure planning; ~40% of these identified measures to target "fauna movement".

Broadly speaking, transport planning may be broken down into four phases (Roberts and Sjölund, 2015). The first is the development of a business case (*concept/investigation phase*). This is overseen by the planning manager and involves the identification of a suitable location for the new infrastructure, including alternatives, risk assessments, *Environmental Impact Assessments* (EIA) and project cost estimations (Tornberg and Odhage, 2018). Once the best location is determined, details regarding how the proposed infrastructure should be designed and built are considered (the *planning/development phase*): for example, road alignment, cross-section, roadside amenities, and other infrastructure (Wu et al., 2017). Planners typically undertake EIA during this stage, partly to help develop an *Environmental Management Plan* (EMP) for the project's construction and operation phases, as well as to manage risks and minimise impacts. Construction can then commence once all relevant details and approvals are obtained, and a contract is awarded (*construction phase*) (Wu et al., 2017). Once completed, the project enters the final stage (*operation/maintenance phase*).

Typically, this process has been dominated by the *technical-rational paradigm*, in which "*the politician and the administrator play clearly defined and non-overlapping roles*" (Marsden and Reardon, 2017). This paradigm does not require the elaboration of planning goals, as it is assumed these are already sufficiently clear to serve as assessment criteria (Tornberg and Odhage, 2018). However, inefficient and flawed assessment practices and procedures can make project goals difficult to achieve (Marsden and Reardon, 2017; Wallace and Jago, 2017; Löfgren et al., 2018; Papp et al., 2022). This is especially true of environmental policy, where integration into the landscape and urban planning are often challenging and contentious (Fu et al., 2016).

For example, transport planners have relied upon EIA to compromise between competing interests through "balancing" the desire for development with the desire for ecological and environmental protection (Fu et al., 2016; Sobolewska–Mikulska, 2019; Papp et al., 2022). However, EIA often takes place in the latter stages of a project, typically once planners have decided on the final location of the planned infrastructure (i.e., the *planning phase*) (Igondova et al., 2016). Despite several published improvements to guide the application of EIA (Igondova et al., 2016; Ulibarri et al., 2019), the use of thematic headings (e.g., natural environment, cultural heritage, etc.) to structure reports often lead to the assessment and mitigation of each in isolation (Löfgren et al., 2018; Bergès et al., 2020). This prevents assessment of cumulative impacts at the broader landscape-scale (Mallard and François, 2013; Igondova et al., 2016; Bergès et al., 2020; Bond et al., 2020). Indeed, EIAs (and road planning in general) typically do not consider the ecological effects of roads and traffic (Jaeger, 2017; Papp et al., 2022).

The introduction of ***Strategic Environmental Assessment*** (SEA) was seen as an improvement because environmental aspects could potentially be integrated into the preparation and adoption of policies, plans and programmes during the early project stages (i.e., in the *concept/planning phases*) (Löfgren et al., 2018; Rega et al., 2018). SEA compliments EIA through the integration of *a-priori* landscape features within infrastructure development, specifically the 'mitigation hierarchy', which enables spatial prioritisation of areas within a development for targeted mitigation and/or restoration activities (Tulloch et al., 2019). As such, the practice of SEA has observed widespread adoption and application, particularly within Europe where it plays a crucial role in keeping environmental concerns central to transport planning (Löfgren et al., 2018).

There is a lack of published literature outlining comprehensive methodologies to guide planners in the application of SEA (Löfgren et al., 2018; Tulloch et al., 2019). In addition to this, Owens *et al.* (in Marsden and Reardon, 2017) regard policy actors and stakeholders as exogenous to the planning process due to the "*separation of powers that exists between the neutral, authoritative experts and the decision-makers whom they advise*" (Marsden and Reardon, 2017, pg. 245). In consequence, these have contributed to suboptimal strategic landscape assessments through the setting of unbalanced objectives and poor integration with the transport planning process (Emberger, 2017; Löfgren et al., 2018; Rega et al., 2018; Papp et al., 2022).

This has led to calls for *communicative rationality*; the enhanced involvement of stakeholders, throughout all stages of the transport planning process (Fu et al., 2016; Johansson et al., 2018), and those with appropriate ecological expertise (Fu et al., 2016). For example, the *Strategic Choice of Measures* (SCM) approach was introduced in Sweden to achieve sustainable transport through improved cost and efficiency of policy measures. This is an informal planning activity premised on a 4-step principle. It involves first identifying and considering measures that affect the need for transport (e.g., regional planning) (step 1), that will result in more efficient use of existing infrastructure (step2), before investing in large reconstruction measures (step 3), or new infrastructure (step 4) (Johansson et al., 2018). The first two steps in particular place heavy emphasis on inter-agency coordination, and collaboration between key stakeholders and actors at the local, regional, and national levels (Tornberg and Odhage, 2018).

Similar strategies have been adopted by other European nations: "concept studies" (Tønnesen in Johansson et al., 2018) and "urban environment agreements" in Norway (Norwegian government in Johansson et al., 2018), and *Sustainable Urban Mobility Plans* (SUMP) in France, Belgium, Italy, Germany, Poland, Scandinavia, UK, and Spain (May 2015; Johansson et al., 2018). More recently, an *Ecological Wisdom Inspired Planning Support System* (EWISPSS) was proposed for use in planning practice in the United Kingdom (Fu et al., 2016). These have in turn acted as conduits for "ecological wisdom", which attempts to replace the traditional views of "*balance*" and "*compromise*" with that of "*integration*" and "*inclusiveness*" (Fu et al., 2016). In other words, ecological wisdom emphasises the need to improve quality of life, as opposed to just human welfare, and its incorporation within planning and practice requires the consideration of economic, social and ecological conditions to be made together (Fu et al., 2016).

There is, however, still considerable progress to be made to advance the ideals of communicative rationality. Indeed, enhanced guidance may only be afforded where a more robust learning culture is adopted (May 2015), where people with various perspectives understand and respect each other (Fu et al., 2016) and the appropriate organisational structures are in place to facilitate this (Simeonova and van der Valk, 2016). Fernstrom *et al.* (in Johansson et al., 2018) showed that while the SCM method could solve transport-related issues, such as stakeholder trust and confidence, it could also have the opposite effect if financial mandates for stakeholder support were narrow and unclear. In the case of SUMPs, May 2015 remarked on the reluctance of governments to approach academia for policy advice. Moreover, while preliminary results of the EWISPSS support the application of holistic ecological wisdom within planning, improved understanding and valuation of indicators used to inform decision-making are needed if an effective implementation is to be achieved (Fu et al., 2016).

Barriers to environmental policies in transportation infrastructure planning

There are three primary causes for environmental policy failure within transport planning. Insights from Europe suggest that the foremost concern is a conflict with the economic interests of involved stakeholders (Gudmundsson and Sørensen, 2013; May 2015). The second was institutionalised interests, mainly about the political motivations of key policy actors (Antonson and Åkerskog, 2015; Emberger, 2017). The final was policy strength, in particular the meaning and quality of the terminology used within the legal context, and the way this was applied (i.e., procedural pathway); these have a profound influence on the interpretation, effectiveness, efficiency, and enforceability of policy by planners and scholars alike (Mallard and François, 2013; Igondova et al., 2016; Enríquez-de-Salamanca, 2018). These are in keeping with previous observations (Howes et al., 2017). Given the strong interplay between each, these can be broadly synthesised into two themes: *conflicts that constrain institutional processes* (i.e., factors that influence the transposition and influence of established policy), and *conflicts that constrain institutional thinking* (i.e., factors that influence information uptake by transport planners and policy actors).

The EU serves as a useful backdrop to the analysis of environmental policy barriers in transport planning as such policies, in particular FSRD, have received widespread legislative support: the *Birds Directive*, *Habitats Directive* and *EIA Directive*. By law, EU Member States are obliged to adopt and implement supra-national (EU) level legislation and policy within their legal systems. However, transposition has been highly heterogeneous, made difficult by the multitude of national and administrative systems that occur between each of the fifteen Member States (Ledoux et al., 2000; Diaz, 2001; Morris, 2011; Papp et al., 2022). Policy transfer restrictions were observed to occur where the language, terminology, and/or ideology behind transport planning policy were not entirely clear, and the language and terminology used within several of the EU Directives have enabled numerous interpretations of each, affecting their passing into law and their efficiency (Ledoux et al., 2000; Marsden et al., 2011; Morris, 2011). Indeed, the multiple interpretations of the term 'biodiversity'; that is the property of an area, the biota of an area, and a preferred end-state (a value), can confuse stakeholders, and incorrect assignment (i.e., "category mistake") may have considerable ramifications on its management (Wallace and Jago, 2017; Papp et al., 2022).

More than half of the Member States failed to achieve the transposition of environmental policy within the 2-year deadline (Diaz, 2001; Morris, 2011), despite the stated policy goal of minimum compliance by several countries (Mallard and François, 2013). For example, a recent investigation into rapid LTI development in Carpathian countries found inconsistent and disjoint national legislation that, in practice, limited the designation, funding, implementation, and enforcement of ecological corridors in road transport projects (Papp et al., 2022). Similarly, non-binding designations that 'protect' natural areas from the influence of transport infrastructure projects are present in both France and Turkey, but their boundaries can be modified or decommissioned to circumvent this (Mallard and François, 2013). Additionally, the United Kingdom (UK), before its exit from the EU in early 2020, adopted a restricted and static interpretation of the EU legal requirements, specifically to not go beyond the minimum requirements of the EU *Directives* "*unless necessary*" (Ledoux et al., 2000; Morris, 2011). Conversely, where transposition was successful, multiple conflicts and high-cost ecosystem management become apparent, especially in instances where member states seek to exceed EU requirements. For example, Germany experienced significant impediments to the implementation of a habitat framework (to comply with Natura2000 requirements), in part due to the absence of an overarching national landscape plan (von Haaren and Reich, 2006). As a consequence, this led each of Germany's 16 federal states to develop plans/concepts independently of one another (with some ignoring EU requirements entirely) (von Haaren and Reich, 2006).

Nature conservation about the development of the road network is regarded to be largely inadequate at the supra-national (EU) level. This is because of the inherent association of conservation laws with habitat fragmentation–i.e., the EU's laws indirectly permitted the continuation of fragmentation (Selva et al., 2011; Apostolopoulou and Adams, 2017). Evidence of this can be seen through the designation of Natura2000 sites; the EU's network of protected sites established under the *Habitats Directive* and *Birds Directive* (Diaz, 2001). The network safeguards ≤2% of national species populations of 'community interest' and birds, but is highly fragmented (Zisenis, 2017). In Germany for example, despite covering 16% of the country, a significant proportion (75%) of low-traffic areas remain unprotected (Selva et al., 2011).

Even in areas where conservation laws do apply, disturbance to these may not necessarily be compensated for through environmental offsets. In many infrastructure projects, it is considered standard practice to deliver environmental offsets where impacts cannot be avoided (Roberts and Sjölund, 2015; Schulp et al., 2016; Weissgerber et al., 2019). Environmental compensation for road and railway projects, however, are reported to be neither well-developed nor widespread (Persson et al., 2015; Apostolopoulou and Adams, 2017). In Sweden, compensation was observed in only 37 projects between 1999 and 2014; these were situations where projects encroached on habitats addressed in the *Swedish Environmental Code* (Persson et al., 2015).

At the project level, transport planners use the mitigation hierarchy, typified through the application of Benefit-Cost-Analysis (BCA), Environment Impact Assessment (EIA), and Strategic Environmental Assessment (SEA), to carefully and systematically evaluate the social, economic and environmental aspects of a project (von Haaren and Reich, 2006; Pettersson, 2013; Wu et al., 2017; Andersson et al., 2018). These tools can be susceptible to manipulation. For example, BCA in Sweden was prone to the 'optimism bias' of transport planners and resulted in substantial underestimation of investment costs and benefits, and environmental consequences, across multiple transport projects in a deliberate attempt to make the project "look good on paper" (Andersson et al., 2018). EIA and SEA are also susceptible to manipulation through the provision of false or exaggerated information, withheld information, incorrect valuation of impacts (i.e., exemption from assessment), and administrative manipulation (Gibson, 2012; Bond et al., 2014; Enríquez-de-Salamanca, 2018; Rega et al., 2018) and administrative disintegration between different institutional sectors (Russel et al., 2018). Moreover, reforms introduced into law in Greece, Canada, Australia, the United Kingdom and South Africa have eroded the practice of these further through the introduction of poor screening and monitoring processes and/or greater discretionary power of assessors (Gibson, 2012; Bond et al., 2014).

This may be in part due to overriding economic interests often associated with transport infrastructure projects (Pettersson, 2013; Akgün et al., 2019). Given that transport accounts for between 10 and 15 per cent of the cost of finished products by European companies (EU, 2021b), there has been a considerable economic imperative to expand the network (Emberger, 2017; Andersson et al., 2018; EU, 2021a). Indeed, expenditure within the transport sector accounted for 2%

of the EU GDP in 2019, or €278 billion (Eurostat, 2021). This position, however, is in stark contrast to the established environmental impacts that result from transport network construction (Forman and Deblinger, 2000; Trocmé, 2005; van der Ree et al., 2015b; Roberts and Sjölund, 2015).

Alternatively, environmental policy failure in transport planning can also occur where a formal procedure(s) is long-established within an institution, giving rise to a disproportionate emphasis on the operation of a particular piece of policy rather than its' outcome. The development of path dependency (i.e., embedded procedural/professional norms) within institutions is well documented in the literature and is linked to several failed attempts to adopt and implement a new policy. For example, the integration of Natura2000 sites into protected area management in central Europe, the role of public participation in environmental knowledge co-production in the United States, and, more recently, improper assessment of transport projects in Sweden due to overreliance on previous experience, and flawed landscape assessment procedures (Antonson and Åkerskog, 2015; Löfgren et al., 2018; Ulibarri et al., 2019).

Additionally, the involvement of multiple stakeholders with different interests, expertise, and viewpoints, and the way these are framed by each, can also have a profound impact on the planning discourse (Marsden and May 2006; Enríquez-de-Salamanca, 2018). This can create extra transactional barriers towards effective policy implementation, especially in the absence of clear and effective communication (Marsden and May 2006; Howes et al., 2017; Akgün et al., 2019). Pettersson (2013), for example, observed a strong focus and prioritisation on the growth paradigm within the Swedish Transport Agency (STA), exemplified through the pre-existing rationality that "*curbing mobility is not an option*", which restricted the consideration of alternative policy options. Similarly, Wu et al. (2017) reported the different interests and conceptualisations of the landscape between three central agencies in Sweden, combined with their unwillingness to negotiate with the others, impeded cross-sector cooperation and resulted in substantial delays to project planning of a major highway (the controversial E6 motorway that passed through the Tanum World Heritage Site).

Political interests play a crucial role in the planning and development of transport infrastructure (Gudmundsson and Sørensen, 2013; Rau et al., 2016). Considerable research effort has been directed towards the direct and transparent dissemination of scientific research, information, and practices into the policy and decision-making processes (Geerlings and Stead, 2003; May 2015; Löfgren et al., 2018; Saarikoski et al., 2018; Tornberg and Odhage, 2018). The availability of information does not necessarily translate into, nor ensure better integration with, policy and decision-making (May 2015; Saarikoski et al., 2018). Transport planners continue to experience low levels of interest and poor engagement with environmental issues from politicians (Löfgren et al., 2018). This is likely due to the strong and overriding ambitions of many politicians to maintain office and power, given the short-term election cycles typical of most democratic systems (Gudmundsson and Sørensen, 2013; Király et al., 2017). Many political actors become susceptible to the "rules of the political game" (see Király et al., 2017, pg. 136). According to Király *et al.* (2017, pg. 137), the rules comprise three filters that encapsulate several mechanisms through which incoming information is filtered and translated before policymaking:

1) Individual–political leaders face cognitive limitations on information processing (e.g., Giddens paradox), as well as issues of accountability in individual decision-making (e.g., blame avoidance and path dependence);
2) Institutional–the political leader is assisted by political institutions and groups; these face challenges of information selection/institutional denial (inaction and denial promote self-justification), and conformity/groupthink (beliefs of leadership are adopted by those lower down in the hierarchy); and,
3) Political–the political sphere is characterised by its rules and incentive structures; the political leader's motivation influences the relative importance of information (group representation), how it is processed, and salience (issue attention cycles), and thus resultant action and policy-making.

Political leaders may be unable to implement more and better sustainable policies, even if they possess all the relevant information (Király et al., 2017). There are two key reasons. The first is that political leaders act on an institutionalised logic of the political arena that restrains their genuine interest to develop sustainable policies. Second, they are actively involved in, and rewarded for, shaping the political arena to maintain political power in the short and medium-term. As such, the dominance of prevailing political interests may have become further entrenched in the European system of governance through a strong emphasis on the institution at an individual level, perpetuated by narrow perspectives, weak/perverse incentives, poor management mechanisms, and competitive professional/departmental cultures within (Geerlings and Stead, 2003).

Finally, strong social perceptions and perspectives are also known to influence decision-makers, especially where transport infrastructure, and their environmental compensation measures, intersect with private property and ownership rights (von Haaren and Reich, 2006; Roberts and Sjölund, 2015). Typically, the general populace will look for certain interests in transport projects and respond more favourably towards land expropriation than conservation (Enríquez-de-Salamanca, 2018; Akgün et al., 2019). Population density and socioeconomic background further influence this: support for LTI projects is limited within high density and socioeconomic level areas, even though these areas may be of less natural value (Enríquez-de-Salamanca, 2018). This was observed in two LTI projects in Spain, where the proposed infrastructures: a high-speed railway and a highway; were re-routed through more environmentally sensitive areas after strong opposition from residents on the grounds of human visual landscape amenity (Enríquez-de-Salamanca, 2018).

Towards FSRD - ecological support tools to achieve improved project outcomes

LTI fragment and degrade landscapes, disrupt natural habitats over considerable distances (the 'road effect zone') and pose a significant threat to wildlife populations, in particular wildlife movement (Forman and Deblinger, 2000; Benítez-López et al., 2010; van der Ree et al., 2015b; Johnson et al., 2017). At least some of these impacts may be alleviated through the enactment of FSRD (van der Ree et al., 2015b). However, few papers in the present SQLR that discussed environmental policies in relation to transportation planning highlighted fauna movement as a concern (see 'Public Institutions' category). Encouragingly, several papers that referred to strategic planning of transportation infrastructure projects in some way highlighted fauna movement as a concern (see "Strategic Planning" category).

There are numerous support tools available to planners that facilitate enhanced capture and integration of environmental aspects, especially FSRD, in project decision-making. Multi-Criteria Decision Making/Multi-Criteria Decision Analysis (MCDM/MCDA) techniques have been used by urban planners to help solve complex decision-making problems, particularly in situations of data uncertainty and ambiguity (Langemeyer et al., 2016; Guaita Martínez et al., 2019). MCDM/MCDA methods have assisted transport planners to make a correct assessment of project environmental impacts (Broniewicz and Ogrodnik, 2020). This is achieved through the five steps critical to the process:

1) Definition of goals and objectives;
2) Identification of decision options;
3. Selection of criteria suitable to monitor goals and objectives (Step 1);
4) Determination of weights for individual criteria; and,
5) Application of procedures and mathematical models to rank options.

(Lammerant et al., 2014)

Several different methods are available, the most popular of which are AHP, TOPSIS, DEMATEL, ELECTRE III/IV, and PROMETHEE (Guaita Martínez et al., 2019; Broniewicz and Ogrodnik, 2020). In particular, MCDM/MCDA has been used to reduce conflicts and increase stakeholder participation in protected area planning and management (Sánchez-Lozano and Bernal-Conesa, 2017; Guaita Martínez et al., 2019), validate project closure planning (Langemeyer et al., 2016), and enhance urban green zone management (Guneroglu et al., 2019).

These, however, are not without their limitations. MCDM/MCDA methods are susceptible to qualitative biases, in particular the subjective process of criteria selection and valuation by stakeholders with divergent interests (Langemeyer et al., 2016; Sánchez-Lozano and Bernal-Conesa, 2017; Guaita Martínez et al., 2019). MCDM/MCDA are also limited in their ability to account for multiple scales of ecosystem services (Langemeyer et al., 2016).

Hybrid or "fuzzy" approaches that combine several methods, or their selected algorithms, may be able to overcome some, but not all model limitations (Guaita Martínez et al., 2019; Broniewicz and Ogrodnik, 2020). This approach, however, typically produces a more complex algorithm that may further limit model usefulness (Broniewicz and Ogrodnik, 2020). Integration of other models may further compound this issue through the introduction of additional limitations. For example, the inclusion of species distribution models (SDMs) may improve the representation of biodiversity features in decision-making (Di Febbraro et al., 2018). SDMs are, however, prone to sampling bias, poor representation of niches and species associations, scale mismatches and insufficient species data (Di Febbraro et al., 2018). Indeed, conservation planners have generally avoided SDMs in favour of simple maps of processes and habitats as proxies for conservation features, even though they may facilitate less robust conservation decisions (Tulloch et al., 2016).

Model outputs may also be improved through the integration of Geographic Information System (GIS) techniques (Antognelli and Vizzari, 2017; Sánchez-Lozano and Bernal-Conesa, 2017). This, however, requires precise quantitative data and the involvement of multiple specialists and specialised software (Broniewicz and Ogrodnik, 2020). Even if resources are to be mobilised, the application of MCDM/MCDA is more than likely to be restricted to large-scale infrastructure projects as smaller-scale projects are less likely to receive the same level of support (McTigue et al., 2018).

The importance of landscape metrics and their calculation

One approach that has started to make a significant real-world impact is the application of various mathematical models of coupled settlement and habitat networks that have gained increased traction (van Strien et al., 2018). Landscape metrics, in

TABLE 1 List of indicators used in the computation of the City Biodiversity Index.

ID	Indicator
1	Proportion of natural areas
2	Connectivity measures or ecological networks to counter fragmentation
3	Native biodiversity in built-up areas (bird species)
4–8	Change in number of native species (optional)
9	Proportion of protected natural areas
10	Proportion of invasive alien species
11	Regulation of quantity of water
12	Climate regulation: carbon storage and cooling effect of vegetation
13–14	Recreational and educational services
15	Budget allocated to biodiversity
16	Number of biodiversity projects implemented annually
17	Rules, regulations, and policy—existence of local biodiversity strategy and action plans
18–19	Institutional capacity
20–21	Participation and partnership
22–23	Education and awareness

particular, may assist transport planners to better visualise the environmental impacts of the transport network (Marucci et al., 2019), develop priorities that inform road function and design (Friedrich, 2017; Psaralexi et al., 2017), and conservation measures that facilitate wildlife movement (Carlier and Moran, 2019a; 2019b). These models are generally user-friendly, do not require complex datasets or species-specific information, and can be adjusted to incorporate new data based on user requirements (van Strien et al., 2018).

The *City Biodiversity Index* (CBI), or *Singapore Index*, is one of the better-known tools used to evaluate and monitor biodiversity within cities (as a proxy for sustainability) (Deslauriers et al., 2018; Sahani and Raghavaswamy, 2018). The index is comprised of 23 indicators (Table 1) proposed for adoption by the National Parks Board of Singapore at the 2012 meeting of the Committee of Parties (COP) in Hyderabad, India (Lammerant et al., 2014; Sahani and Raghavaswamy, 2018). Each indicator is given a score out of four (0–4), where 0 corresponds to poor performance and four to excellent performance. These scores can be summed to provide an overall score of the city's biodiversity performance (Lammerant et al., 2014). Indicator two of the CBI relates to the connectivity of natural areas in cities, and can be used to develop and evaluate the effectiveness of green infrastructure (e.g., vegetated corridors) that link habitat fragments (Deslauriers et al., 2018). This is calculated through the equation:

$$IND2_{CBI} = Total\ area\ of\ natural\ areas\ that\ are\ connected\ (\leq 100m\ apart)/Total\ area\ of\ natural\ areas$$

Source: Deslauriers et al., 2018, pg. 101.

Although simple to calculate, the strength of the CBI is dependent on the appropriate designation of "natural" landscape features (i.e., where natural processes dominate); incorrect assignment may have considerable impact results (Deslauriers et al., 2018). Some examples of "natural" landscapes that are easy to assign include mangroves, forests, wetlands, grasslands, and rivers. Harder to assign are artificial landscapes, such as parks, golf courses and vegetated roadside verges, which do not necessarily constitute 'natural areas' unless natural ecosystems dominated by native species are present (Deslauriers et al., 2018). The CBI, however, does not adequately address overall connectivity as it does not account for small barriers (<100 m width) or the presence of structures that impede movements inside fragments (i.e., within-patch connectivity) (Deslauriers et al., 2018). Indeed, Freeman-Cole and Jaeger (2020) have observed greater connectivity in more highly fragmented patches.

Landscape connectivity may be more reliably measured with *effective mesh size* (m_{eff}). This metric measures the probability that any two randomly chosen points within a landscape are connected, and represents the average amount of habitat that is accessible to an individual when placed at random on a landscape (Torres et al., 2016; De Montis et al., 2018; Deslauriers et al., 2018; Spanowicz and Jaeger, 2019; Freeman-Cole and Jaeger, 2020). This is represented by:

$$m = \frac{A_t}{S} = \frac{1}{A_t}\sum_{i=1}^{n} A_i^2$$

Source: Chailloux *et al.* (2020), pg. 3

This divides the landscape up into n patches. Patch areas are denoted by A_i, with $1 \leq i \leq n$ (Chailloux et al., 2020). A_t represents the total area of a region. S represents the splitting index; this is the number of patches that result from the division of the landscape into meshes of equal size:

$$S = \frac{A_t^2}{\sum_{i=1}^{n} A_i^2}$$

Source: Chailloux *et al.* (2020), pg. 3

The metric is highly versatile and has been modified by several authors to address a range of scenarios, such as: measuring road and noise impacts on birds populations (Cuervo and Moller, 2020; Konstantopoulos et al., 2020), landscape connectivity (Deslauriers et al., 2018; Spanowicz and Jaeger, 2019), the impact of conservation measures (De Montis et al., 2018), urban sprawl (Torres et al., 2016; Canedoli et al., 2018), and regional planning (Girvetz et al., 2008; Jaeger et al., 2008). Importantly, effective mesh-size accounts for within-patch connectivity and is, therefore, a more reliable indicator of connectivity compared to the previous $IND2_{CBI}$ (Deslauriers et al., 2018).

Other landscape metrics have been developed for use in urban and transport planning: *Infrastructural Fragmentation Index* (IFI) (De Montis et al., 2018); *Area Weighted Metric* and *Integral Index of Connectivity* (Ascensão et al., 2019); *Road Permeability Index* (RPI) (Assis et al., 2019); *Roadless Fragmentation Indicator* (RFI) (Kati et al., 2020); *Spatial Road Disturbance Index* (SPROADI) (Nematollahi et al., 2017); *Probability of Connectivity Index* (PC) (Furberg et al., 2020); *Incidence Function Model* (IFM) (Graham et al., 2018); and *Least Cost Paths* (LCP) (Balbi et al., 2019). Several of these, especially the Connectance Index (*CONNECT*) and Number of Links (*NL*), however, are unreliable as measures of landscape connectivity (Spanowicz and Jaeger, 2019; Freeman-Cole and Jaeger, 2020).

Implications and future directions

LTI planning is a transdisciplinary field that requires cross-sectional dialogue and cooperation. Road ecology is the embodiment of this, bringing together research insights from a range of disciplines from which new methodologies, techniques and approaches emerge. This study, to the knowledge of the authors, is one of only two studies that explore the science-policy interface between FSRD and transport infrastructure planning. A recent article found ecological corridors were generally not well represented in national legislation or planning practice in the Carpathian Mountains (Papp et al., 2022). The authors made a series of recommendations to improve the long-term harmonisation of grey and green infrastructure, including enhanced and sustained stakeholder dialogue, participation and cooperation, legislative harmonisation of biodiversity terminology, especially ecological corridor/network and sustainable transport development, and development of improved project assessment techniques (e.g., EIA and SEA) (Papp et al., 2022).

The primary focus of their study, however, was to examine LTI development within the Carpathian ecoregion. The present study builds on the findings of Papp *et al.* (2022) through a broader spatial and temporal analysis of the available transport planning and policy research. A key finding was the lack of reference made within this literature to the detrimental impacts that LTI have on wildlife, especially wildlife movement, nor the solutions required to mitigate these (i.e., fauna-sensitive road design). Both are already widely acknowledged in road ecology research (Kociolek et al., 2011; Pell and Jones, 2015; Johnson et al., 2017; Johnson et al., 2022; Papp et al., 2022).

Moreover, there was limited research available to indicate meaningful integration of FSRD measures in road projects by transport policy- and decision-makers (but see Papp et al., 2022). A broader analysis of the integration of environmental policies into transport planning, however, suggests this to be highly unlikely given the multitude of competing sector interests, different political objectives and incorrect policy interpretations that continue to dominate these sectors.

Encouragingly, aspects of FSRD, in particular fauna movement, were more frequently referred to in papers that discussed strategic planning within transport infrastructure planning. Importantly, numerous support tools are available to transport planners that facilitate enhanced capture and integration of environmental aspects, especially FSRD, in project decision-making. Of promise are the mathematical models, such as *effective mesh size* (m_{eff}), that can assist transport planners to visualise wildlife settlement and habitat networks for targeted management.

Several limitations, however, are acknowledged in the present study. First, this SQLR sought to synthesise and articulate gaps within the available scholarly literature. Its purpose was not to critically examine and evaluate the translation of FSRD measures from research into practice by government institutions. Second, this SQLR was limited to the studies identified by search terms, databases and language (English) established in the search protocol. Peer-reviewed papers retained in this review were further limited to literature published within Anglo-European countries (Europe, Australia, United Kingdom and Canada). Undoubtedly, there were studies excluded and or missed from this process, especially those in grey literature and non-English languages. These may have provided greater illumination of the contemporary and applied experiences of transport planners and decision-makers. Nonetheless, we do contend that most of this knowledge has already been captured in English peer-reviewed literature, as is the case for literature on road ecology (Fahrig and Rytwinski, 2009; Benítez-López et al., 2010; Johnson et al., 2022). We are therefore confident that the quantity and variety of papers included in this review are reflective of current and emerging practices in Anglo-European transport infrastructure planning. Despite these, the findings of this SQLR have a considerable bearing not only on the design and management of road corridors but also on land management practices more broadly.

Importantly, two key recommendations have emerged. First, transport researchers and practitioners need to recognise and acknowledge that LTIs have considerable long-term, cumulative negative impacts on wildlife. This is necessary if meaningful adoption and implementation of FSRD measures in road transportation planning are to occur. Second, there is a clear gap in our understanding that surrounds the uptake and adoption of road ecology research by both transport planning and policy researchers and transport practitioners. While the results of the present study were insufficient to determine how well defragmentation policies, such as FSRD, had been integrated into transportation infrastructure policy, there was some evidence (through reference to supra-national EU legislation and policy) to suggest this has not led to substantive change in institutional planning practices.

As such, there is an opportunity for 'action-oriented' research that will improve the transfer of scientific knowledge into policy outcomes. This research should seek to apply dual methodological approaches that:

A) examine and critically appraise defragmentation and or FSRD policy documents; and,

B) make a direct inquiry about the individual experiences of transport practitioners, either through surveys or interviews.

Such an approach would not only assist in the identification of overall familiarity with the topic of road ecology and FSRD, but also the illumination of professional and political pressures that influence practitioners and decision-makers involved in transportation infrastructure projects. Without this level of understanding, the continued push to develop a sustainable transport network, where environmental concerns are balanced against economic and social outcomes, may as well be a road to nowhere.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

Conceived the SQLR: CJ, TM, and DJ. Performed the SQLR: CJ. Analysed the data: CJ. Contributed materials/critique/analysis tools: CJ, TM, MB, and DJ. Wrote, formatted, and edited the paper: CJ, TM, MB, and DJ.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary Material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.959918/full#supplementary-material

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