

# Roadside grassland restoration: Challenges and opportunities in the UN decade on ecosystem restoration

Orsolya Valkó<sup>1,2</sup>, Réka Fekete<sup>1,3,4</sup>, Attila Molnár V<sup>3,4</sup>,  
Melinda Halassy<sup>2,5</sup> and Balázs Deák<sup>1,2</sup>

## Abstract

Restoring near-natural grasslands on roadsides is an excellent opportunity to support native biodiversity and provide ecosystem services that benefit the safety and functionality of road networks. Although several best practices and case studies are available on biodiversity-friendly roadside revegetation measures, their application is quite scarce, and, in practice, ecological aspects are rarely considered. To restore and preserve diverse and native roadside vegetation, we suggest (1) facilitating discussion, cooperation, and knowledge transfer between ecologists and agencies responsible for roadside vegetation management, (2) prioritizing the use of native plant species in roadside restoration and revegetation, as well as increasing regional capacities for native seed production, (3) supporting the application of biodiversity-friendly management practices of roadside vegetation, and (4) inventorying and conserving remnant semi-natural roadside grasslands.

## Addresses

<sup>1</sup> 'Lendület' Seed Ecology Research Group, Institute of Ecology and Botany, Centre for Ecological Research, 2-4 Alkotmány Street, H-2163 Vácrtót, Hungary

<sup>2</sup> National Laboratory for Health Security, Centre for Ecological Research, 29 Karolina Street, H-1113 Budapest, Hungary

<sup>3</sup> ELKH-DE Conservation Biology Research Group, 1 Egyetem Sq., H-4032 Debrecen, Hungary

<sup>4</sup> Department of Botany, Faculty of Sciences & Technology, University of Debrecen, 1 Egyetem Sq., H-4032 Debrecen, Hungary

<sup>5</sup> Institute of Ecology and Botany, Centre for Ecological Research, 2-4 Alkotmány Street, H-2163 Vácrtót, Hungary

Corresponding author: Valkó, Orsolya ([valkoorsi@gmail.com](mailto:valkoorsi@gmail.com))

Current Opinion in Environmental Science & Health 2023, 34:100490

This review comes from a themed issue on **Environmental Impact Assessment: Nature based solutions**

Edited by Paulo Pereira, Carla Sofia Ferreira and W. Zhao

For complete overview of the section, please refer to the article collection - [Environmental Impact Assessment 2023: Nature based solutions](#)

<https://doi.org/10.1016/j.coesh.2023.100490>

2468-5844/© 2023 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

## Keywords

Ecological restoration, Green infrastructure, Invasive alien species, Rights-of-way infrastructure, Road ecology, Road verge.

## Introduction

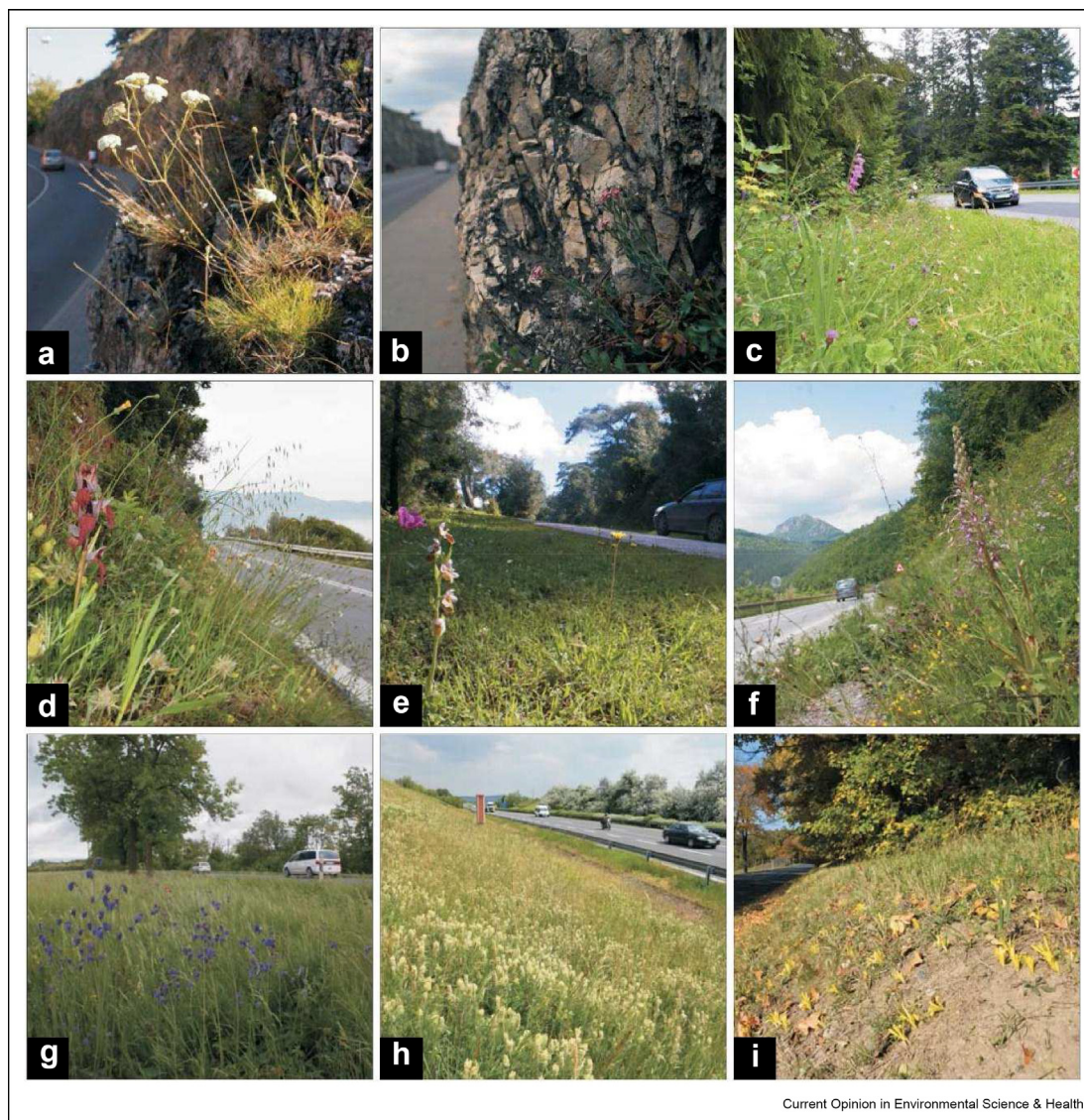
The UN Decade on Ecosystem Restoration (2021–2030) offers unprecedented opportunities to halt negative human impacts on biodiversity and restore global ecosystems. Global restoration ambitions pose great challenges, as several theoretical and practical issues need to be tackled for maximizing biodiversity benefits from the planned actions [1]. Because of the limited resources in the nature conservation sector, it is key to identify synergies where conservationists can act jointly with other sectors, and restoration outcomes provide win–win solutions for multiple stakeholders [2]. Such a field might be the restoration of roadside vegetation. The total global road network is longer than 64 million km and continuously increasing [3], with the roadsides covering approximately 1% of the surface of developed countries [4]. While the revegetation of roadsides and maintenance of permanent vegetation are an important task for road managers, roadsides could be plausible places for the restoration of grasslands that otherwise are neglected in most restoration agendas despite their global decline, high biodiversity, and potential in the delivery of ecosystem services [5–8].

The objective of this opinion paper is to evaluate current trends and future perspectives in roadside grassland restoration. First, the specifics of roadside grassland restoration compared to non-roadside areas are discussed. Second, we briefly introduce the current state-of-the-art of roadside revegetation, highlight some of the best practices available, and emphasize the need for their wide adoption. Third, we discuss trade-offs and synergies in roadside grassland restoration. Finally, we identify the most important knowledge gaps and the most pressing practical challenges that need to be addressed in the field.

## Vegetation of roadside grasslands and specific challenges related to their restoration

The structure and species composition of roadside grasslands depends on their origin, bedrock, topographic and climatic factors, landscape context, and management (Appendix 1). Globally, many roadside areas hold degraded vegetation and harbor non-native species, including several invasive alien plants [9,10]. The

Figure 1



Current Opinion in Environmental Science &amp; Health

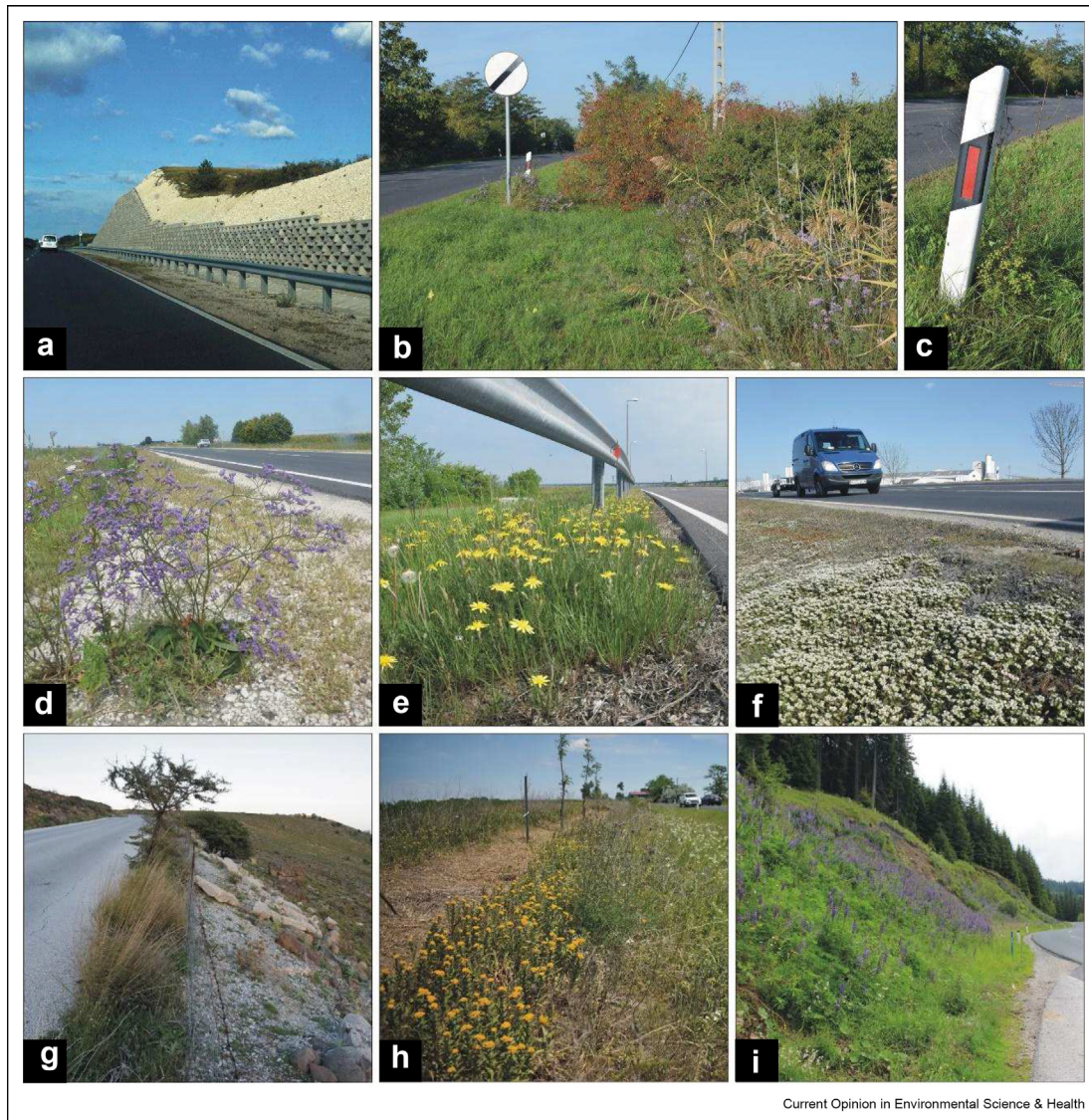
Roadsides provide safe havens for several endangered plant species in many parts of the world. Rocky outcrops on roadside provide habitat for the Pannonian strict endemic species *Seseli leucospermum* (panel a) and to the sub-Mediterranean flora element *Aethionema saxatile* (panel b) in the Transdanubian mountain range, Hungary. Mown roadside verges provide refugia for endangered species of hay meadows, such as *Gladiolus imbricatus* in the Tatra mountains, Poland (panel c). Roadsides in the Mediterranean harbor several orchid species, such as *Serapias cordigera* (Lesbos, Greece, panel d), *Ophrys lesbis* (Turkey, panel e), and *Himantoglossum calcaratum* (Bosnia & Herzegovina, panel f). Rare and endangered species of loess steppes can also find refugia in roadsides: *Salvia nutans*, *Oxytropis pilosa*, and *Sterbergia colchiciflora* (panels g, h, i, respectively) in Hungary. Photo credits: Attila Molnár V.

remnants of native grassland vegetation along the roadsides are less abundant but indeed act as important reservoirs of biodiversity, especially in agricultural or urban landscapes [11–13], and potentially provide safe havens for several protected species [14,15] (Figure 1). Because these areas are usually not fertilized, they often harbor less competitive native species. Because of the intensification of agricultural, industrial, and urban development, grasslands are being plowed, built upon, or afforested at an alarming rate in many regions,

implying that the role of roadsides in providing safe havens for grassland species will become even more important in the future [15,16]. Roadsides play an essential role in maintaining landscape-scale ecological processes and ecosystem services [17,18] (Appendix 2). Considering the abovementioned importance of near-natural grasslands on roadsides, their restoration can result in several positive outcomes, especially considering that roadsides are among the most accessible options for establishing green infrastructure [19]. They



Figure 2



Current Opinion in Environmental Science &amp; Health

Special characteristics of roadside environments. Concrete elements used for erosion control prevent the establishment of native plant species on roadsides (panel a). Regular mowing of roadside verges prevents shrub encroachment but also decreases the reproductive success of grassland-specialist forb species (panel b). These species have better reproductive success next to light-reflecting columns, that are protected from mowing (panel c). The use of de-icing salts supports the establishment of halophyte plants on roadsides, including native species of alkaline grasslands, such as *Limonium gmelinii* subsp. *hungaricum* (panel d), *Podospermum canum* (panel e), and species originating from distant seashore regions, such as *Cochlearia danica* (panel f). Roadsides often form a continuum with surrounding habitats and can enjoy protection from overgrazing (panel g). Afforestation of roadsides with non-native woody species represents a major threat for the remnant grassland vegetation (panel h). Roadsides are corridors for the spread of invasive alien species, such as *Lupinus* spp. (panel i). Photo credits: Attila Molnár V. (panels a–g), Szabolcs Kis (panel h), and Réka Fekete (panel i).

provide an opportunity to establish high-diversity landscape features, in line with the objectives of the EU Biodiversity Strategy [20], and to improve the connectivity of natural habitats in cleared and transformed landscapes.

Roadsides represent a unique and harsh environment that is different in many aspects from natural habitats

(Figure 2). The use of roads and the maintenance of roadsides are associated with frequent and severe disturbances that shape roadside environments [3]. Several biotic, edaphic, and microclimatic factors act as strong environmental filters that hinder the establishment of target plant species on roadsides. Traffic is a major source of pollution, including NO<sub>x</sub> deposition from vehicles [3]. This, coupled with the role of vehicles in the

seed dispersal of invasive alien species [21], makes roadsides hotspots for plant invasions. The disturbance related to road use and maintenance facilitates the fast spread of these species [3] and fosters rapid colonization of new areas, which presents a great challenge for the establishment of native target species on roadsides [22]. Roadsides often have unstructured and degraded soil, which due to its compactness hampers the establishment of several plant species [3]. Maintenance of roads involves the use of deicing salts, which, together with compacted soil, provide suitable establishment conditions for several salt-tolerant or halophyte species [23,24] and hinder the establishment of salt-intolerant plants in the vicinity of the road edge. Gradients in disturbance, microtopography, and microclimate are major drivers of roadside vegetation composition. Therefore, despite being narrow structures, there is often a vegetation zonation from the road edge to the neighboring habitat [25]. There may be large differences between the microclimate on the north- and south-facing slopes of the roadsides. Steep south-facing slopes provide an extremely harsh environment that can be further aggravated by the aridity of the macroclimate and by ongoing climatic changes [26].

The above examples illustrate that roadsides are different from non-roadside areas in many aspects, so restoration guidelines need to be fine-tuned for this specific environmental context [27]. Microsite preparation measures including erosion control, substrate amelioration, and surface roughing techniques [28] that are often necessary to improve the habitat conditions on roadsides so that the sown or spontaneously incoming propagules can have a chance of germination and establishment.

The primary function of roadsides is related to transportation; therefore, roadside restoration projects must be planned in accordance with traffic safety and road network functionality [29]. Road managers have their own priorities regarding the timing and costs, as well as manpower and machinery available for interventions, and they also have their own preferences for the type and structure of the roadside vegetation. Therefore, it is crucial to evaluate current roadside revegetation practices and identify trade-offs and synergies between biodiversity conservation and road management (see Section [Trade-offs and synergies](#)).

### Current practices in roadside revegetation

Several best practices and case studies are available on the restoration of near-natural grasslands on roadsides. However, these are considered in roadside revegetation projects (aiming to establish permanent vegetation cover on roadsides without specific biodiversity conservation preferences) only in certain regions, such as parts of Europe and North America [30]. A shift would be

The ecological basis for the selection of the suitable target species is well established ([Box 2](#)), and there is a large technological development regarding the application of different roadside restoration practices [28]. However, there are some major knowledge gaps related to the long-term sustainability and performance of restored vegetation. Some of the research areas which we consider the most important in the future are listed below.

#### Box 1. Knowledge gaps and research needs

- ❖ There is a geographic bias toward temperate regions in the research of roadside restoration; thus, studies in other regions would be needed.
- ❖ There is a taxonomic bias in studies on roadside restoration as most of them focus on established plant species, or some flagship animal groups such as pollinators and birds, but studies on other taxa are scarce. Multitaxon studies, involving less studied animal groups and soil microbiota, would be essential for a comprehensive evaluation of restoration success and ecosystem functioning.
- ❖ There is very little knowledge about the long-term vegetation development in roadside restoration. Long-term studies and chronosequence analyses would be necessary to evaluate the development of the vegetation, as well as the ecosystem services and functions on restored roadsides.
- ❖ More studies would be needed on ecosystem services provided by restored roadsides to provide evidence and encouragement for decision-makers and site managers to apply biodiversity-friendly practices. Detailed cost-benefit analyses are necessary to better understand the practical applicability of nature-based solutions in roadside restoration. There is also a lack of studies on the spillover of ecosystem services from restored roadsides toward adjacent areas.
- ❖ Studies should carefully assess whether there is a threat of creating ecological traps when restoring roadsides. Is there a width threshold that is needed to buffer the negative environmental effects of roads or adjacent hostile habitats on the restored roadside ecosystem? In addition, research should address how the proper design of roadside vegetation can decrease the chance of animal-vehicle collisions.
- ❖ It is necessary to understand how to make roadside restoration more practical and widespread in practice. This involves the need for multidisciplinary studies based on the cooperation of roadside managers, social scientists, economic experts, and ecologists.
- ❖ Roadside environments are expected to be increasingly influenced by climate change, increased traffic, and intensified land use in neighboring habitats. How do these drivers alone or in interaction affect the trajectory of roadside vegetation assembly, and how can restoration measures be adapted to cope with the changing environment?



### Box 2. Selecting native target species for roadside restoration

To select the best native species for roadside restoration, several aspects must be considered, including the environmental conditions of the roadsides and the presence of particular microsites along the roadside slopes, plant traits that make species able to establish and survive, and the distribution range and availability of the target species. In revegetation projects, commercial seed mixtures are widely used. These mixtures can perform sufficiently in temperate and humid macro- and microclimate (typical to north-facing slopes) and on less compacted soil, but they are less adequate in arid climates (mostly typical on south-facing slopes) and on silty or clayey soil [45]. In the latter harsh environments, the establishment success and persistence of plants seeded by commercial seed mixtures are usually low [26]. To overcome the challenge posed by the co-occurrence of contrasting environments, the application of well-tailored, adaptive seed mixtures can be a feasible solution. In practice, road managers would need to be given a set of key different restoration options (e.g., seed mixtures recommended for south-facing and north-facing road slopes in a biogeographical region) that they can use, depending on the local context.

Using a trait-based approach, under the Mediterranean climate, using fast-growing competitor species with high specific leaf area on milder north-facing slopes has been suggested [46]. On south-facing slopes, the use of plants tolerating high environmental stress was recommended; the most successful candidates were species whose seeds are resistant to removal by water runoff and those that have a mucilaginous seed coat that provides resistance to drought. On steep slopes, especially on south-facing ones, the ability of plants to control erosion should also be considered [47]. In a boreal region, the use of species with low stature, widespread above- and belowground parts, a perennial life-cycle, and drought-tolerant properties, has been recommended [25].

To select the best candidates for grassland restoration, ecologically adapted native species from the regional species pool should be considered when possible. An option is to select candidates from the species pool of the environmentally similar habitats in the region [48]. Another option is to select candidates from native plants that naturally occur on roadsides [25,49]. Several studies highlight the great capacity for natural colonization of roadside slopes by spontaneous succession from surrounding areas, suggesting a potential for passive recovery [30,31,50]. Therefore, the maintenance of well-conserved natural areas close to the roadsides can enhance plant compositional changes toward the desired states in recovering roadsides [26]. The composition and quantity of seed mixtures should fit into the landscape context: more diverse seed mixtures and higher sowing density are needed in cleared and transformed landscapes that lack propagule sources for spontaneous colonization [31,51].



Native generalist species such as *Medicago minima*, *Festuca pseudovina*, *Salvia verticillata*, and *Sanguisorba minor* (from left to right) can be suitable candidates for roadside revegetation. Photo credits: Attila Molnár V.

needed to prioritize multifunctional, near-natural roadside grasslands composed of native species in most regions of the world. To achieve this goal, the available best practices for their restoration and management should be applied, and important knowledge gaps should be addressed (Box 1).

One of the most widely used methods in roadside revegetation is the hydroseeding of commercial mixtures that are mainly composed of highly competitive forage grasses and legumes non-native to the areas [26]. Commercial seed mixtures are widely available, but perform much worse than regional native seed mixtures. Especially under harsh macro- or microclimate, commercial species often fail to establish or do not provide a sufficient and permanent vegetation cover and fail to

provide erosion control services without the expensive use of fertilizers and irrigation [26,31]. Thus, a shift from commercial seed mixtures toward tailor-made regional native seed mixtures would be essential (see Box 2). The proper selection of target species can support the delivery of particular functions. For instance, the frequency of animal-vehicle collisions can be decreased if short native plants that are not palatable or not attractive to large mammals are used [32].

### Trade-offs and synergies

As resources are limited, there is a trade-off between biodiversity and cost-effectiveness in roadside revegetation programs. The propagules of native species are often expensive or have limited availability in many

regions [33]; therefore, in practice, it is often only possible to use a limited number of native species. Native species that are adapted to the site conditions can provide and maintain a permanent vegetation cover; therefore, it improves water infiltration, reduces soil erosion and deflation, as well as can mitigate the encroachment of invasive alien species. Therefore, when a high species richness cannot be achieved, the use of a moderate number of native species can provide the required ecosystem functions and be a more feasible option than the use of commercial seed mixtures.

There are also trade-offs regarding the habitat quality of restored grasslands. As roadsides are narrow and fragile ecosystems adjacent to the hostile environment of roads, creating ecological traps should be avoided. The trade-off between improved habitat quality for animals and increased risk of animal-vehicle collisions should be considered [34]. Also, road manager authorities usually prefer not to have rare organisms on roadsides, as these can result in serious legal impediments for maintenance work and road widening.

In addition to trade-offs, there are also synergies between the objectives of road managers and restoration ecologists. Near-natural grasslands with low maintenance frequency and low to medium sward height represent an ideal vegetation type for both stakeholder groups. In such vegetation, maintenance costs can be reduced, and traffic safety can be improved: improved visibility of animals reduces the chance of animal-vehicle collisions on grassy roadsides and branches falling from trees do not represent traffic safety issues there [18]. Grasslands on roadsides can provide permanent vegetation cover and decrease the rate of erosion or deflation, which also contributes to the safety and functionality of road networks.

## Conclusions and implications for practice

The extent and expansion of global road networks imply the need for large-scale roadside revegetation projects, which offer a possibility of restoring near-natural grasslands on roadsides. The available evidence shows that preserving and restoring near-natural grasslands on roadsides can have several positive outcomes that go beyond the local scale [18]. It is clear, however, that grassland restoration is not plausible on all roadsides, because of several social and economic challenges, specific site conditions, or the lack of native propagule sources. The combination of stakeholder surveys, GIS methods, and mathematical modeling can support spatial planning and prioritization [35]. Restoring roadsides in and around protected areas and other high nature value sites should be prioritized [36]. They could also serve as an effective mitigation measure against the infiltration of invasive alien species into protected areas.

In addition to assigning roadside sections for grassland restoration, inventory and conservation of the existing remnant high nature value habitats on the roadsides are also an important task [12,37,38]. Special emphasis should be given to old, historical verges which usually hold the highest biodiversity [12]. At these sites, early detection and control of invasive alien species are especially important.

Facilitating discussion and cooperation between ecologists and agencies responsible for roadside vegetation management would be crucial. It is important to understand the attitudes of stakeholders and decision-makers' and their perceived benefits and barriers to near-natural grassland restoration and management on the roadsides [39]. Additionally, more effective knowledge transfer to stakeholders and decision-makers is necessary about the importance and benefits of restoring near-natural grasslands along roadsides. A study involving Iowan decision-makers showed that those decision-makers who regularly consulted with a roadside vegetation manager were more open to choosing biodiversity-friendly management practices and valued the positive outcomes on pollinators and wildlife more [39]. Brochures and information material about choosing the proper native species for introduction and about biodiversity-friendly roadside management practices are also much needed. Since roadsides are usually state-owned, engaging decision-makers is crucial. It is an advantage that the restoration of these areas is often possible without negotiations with multiple owners [40].

Increasing regional capacities for native seed production would be a much-needed step forward in the transition to using nature-based solutions in roadside restoration [33,41]. This support would be essential for making native seed mixtures an available and affordable alternative to commercial mixtures. The application of seed enhancement technologies, such as seed priming and seed coating, could considerably improve the establishment of sown target species affected by harsh environmental conditions typical of roadsides, but to evaluate the potential of these, studies would be needed to upscale the most promising technologies [42].

After restoration, maintaining regular mowing management to remove biomass and prevent succession to forests [27] is of vital importance. In general, the application of an intermediate mowing frequency, fitted to the regional climatic and landscape context, is recommended. Reduction of mowing frequency can save costs and can reduce traffic jams typical during such operations and can also support higher biodiversity compared to unmown and too frequently mown areas [43]. In areas specifically dedicated to biodiversity conservation, management measures must be

harmonized to meet the requirements of different species groups [44].

## Declaration of competing interest

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

## Data availability

No data was used for the research described in the article.

## Acknowledgements

The work of the authors was supported by the Hungarian National Research, Development and Innovation Office (O. Valkó – NKFI KKP 144096, B. Deák – NKFI FK 135329, R. Fekete – NKFI PD 143425, A. Molnár V. – NKFI K 132573., M. Halassy – NKFI K 138060). This research was supported by the National Research, Development and Innovation Office within the framework of the National Laboratory for Health Security programme (RRF-2.3.1-21-2022-00006). The research was funded by the Sustainable Development and Technologies National Programme of the Hungarian Academy of Sciences (FFT NP FTA). The authors thank Szabolcs Kis for providing photos for the figures.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.coesh.2023.100490>.

## References

- Cliquet A, Telesetsky A, Akhtar-Khavari A, Declerck K: **Upscaling ecological restoration: toward a new legal principle and protocol on ecological restoration in international law.** *Restor Ecol* 2022, **30**, e13560.
- This is a key paper that proposes standards and legal principles that can maximise the positive impacts of the UN Decade on Ecosystem Restoration.
- Aronson J, Goodwin N, Orlando L, Eisenberg C, Cross AT: **A world of possibilities: six restoration strategies to support the United Nations Decade on Ecosystem Restoration.** *Restor Ecol* 2020, **28**:730–736.
- van der Ree R, Smith DJ, Grilo C: *Handbook of road ecology.* Wiley-Blackwell; 2015.
- Forman RTT: **Estimate of the area affected ecologically by the road system in the United States.** *Conserv Biol* 2000, **14**: 31–35.
- Dudley N, Eufemia L, Fleckenstein M, Periago ME, Petersen I, Timmers JF: **Grasslands and savannahs in the UN decade on ecosystem restoration.** *Restor Ecol* 2020, **28**:1313–1317.
- Bardgett RD, Bullock JM, Lavorel S, Manning P, Schaffner U, Ostle N, Chomel M, Durigan G, Fry EL, Johnson D, *et al.*: **Combating global grassland degradation.** *Nat Rev Earth Environ* 2021, **2**:720–735.
- Buisson E, Archibald S, Fidelis A, Suding KN: **Ancient grasslands guide ambitious goals in grassland restoration.** *Science* 2022, **377**:594–598.
- This is a key paper that emphasises the importance of grassland ecosystems in restoration ambitions and calls for more appreciation of this important ecosystem.
- Tölgyesi C, Buisson E, Helm A, Temperton VM, Török P: **Urgent need for updating the slogan of global climate actions from “tree planting” to “restore native vegetation.”.** *Restor Ecol* 2022, **30**, e13594.
- Lázaro-Lobo A, Ervin GN: **A global examination on the differential impacts of roadsides on native vs. exotic and weedy plant species.** *Global Ecol Conserv* 2019, **17**, e00555.
- Pérez-Postigo I, Bendix J, Vibrans H, Cuevas-Guzmán R: **Diversity of alien roadside herbs along an elevational gradient in Western Mexico.** *NeoBiota* 2021, **65**:71–91.
- Johansen L, Henriksen MV, Wehn S: **The contribution of alternative habitats for conservation of plant species associated with threatened semi-natural grasslands.** *Ecol Solutions Evidence* 2022, **3**, e12183.
- Auffret AG, Lindgren E: **Roadside diversity in relation to age and surrounding source habitat: evidence for long time lags in valuable green infrastructure.** *Ecol Solutions Evidence* 2020, **1**, e12005.
- Deák B, Rádai Z, Lukács K, Kelemen A, Kiss R, Bátori Z, Kiss PJ, Valkó O: **Fragmented dry grasslands preserve unique components of species and phylogenetic diversity in agricultural landscapes.** *Biodivers Conserv* 2020, **29**:4091–4110.
- Fekete R, Bódis J, Fülöp B, Süveges K, Urgyán R, Malkócs T, Vincze O, Silva L, Molnár VA: **Roadsides provide refuge for orchids: characteristic of the surrounding landscape.** *Ecol Evol* 2020, **10**:13236–13247.
- Vanneste T, Govaert S, De Kesel W, Van Den Berge S, Vangansbeke P, Meeussen C, Brunet J, Cousins SA, Decocq G, Diekmann M, Graae BJ: **Plant diversity in hedgerows and road verges across Europe.** *J Appl Ecol* 2020, **57**:1244–1257.
- Quédraogo DY, Villemey A, Vanpeene S, Coulon A, Azambourg V, Hulard M, Guinard E, Bertheau Y, Flamerie De Lachapelle F, Ruel V, Le Mitouard E: **Can linear transportation infrastructure verges constitute a habitat and/or a corridor for vertebrates in temperate ecosystems? A systematic review.** *Environ Evid* 2020, **9**:1–34.
- Ding J, Eldridge DJ: **Roadside verges support greater ecosystem functions than adjacent agricultural land in a grassy woodland.** *J Environ Manag* 2022, **308**, 114625.
- Phillips BB, Bullock JM, Osborne JL, Gaston KJ: **Ecosystem service provision by road verges.** *J Appl Ecol* 2020, **57**:488–501.
- Filazzola A, Shrestha N, MacIvor JS: **The contribution of constructed green infrastructure to urban biodiversity: a synthesis and meta-analysis.** *J Appl Ecol* 2019, **56**: 2131–2143.
- Elmqvist T, Valkó O, Walloe L, Smagghe G, Van Montagu M, Mihailova M, Yovchevska P, Basic F, Prach K, Baldassarre Svecova E, *et al.*: *EASAC policy report 44: regenerative agriculture in Europe: a critical analysis of contributors to European union farm to fork and biodiversity strategies.* 2022.
- Yang M, Pickering CM, Xu L, Lin X: **Tourist vehicle as a selective mechanism for plant dispersal: evidence from a national park in the eastern Himalaya.** *J Environ Manag* 2021, **285**, 112109.
- This experimental study showed the great potential of vehicles in seed dispersal and in the spread of invasive alien species along roads.
- Benedetti Y, Morelli F: **Spatial mismatch analysis among hotspots of alien plant species, road and railway networks in Germany and Austria.** *PLoS One* 2017, **12**, e0183691.
- Fekete R, Haszonits G, Schmidt D, Bak H, Vincze O, Süveges K, Molnár VA: **Rapid continental spread of a salt-tolerant plant along the European road network.** *Biol Invasions* 2021, **23**: 2661–2674.
- Fekete R, Bak H, Vincze O, Süveges K, Molnár VA: **Road traffic and landscape characteristics predict the occurrence of native halophytes on roadside verges.** *Sci Rep* 2022, **12**:1–12.
- Karim MN, Mallik AU: **Roadside revegetation by native plants: I. Roadside microhabitats, floristic zonation and species traits.** *Ecol Eng* 2008, **32**:222–237.
- García-Palacios P, Soliveres S, Maestre FT, Escudero A, Castiello-Monroy AP, Valladares F: **Dominant plant species modulate responses to hydroseeding, irrigation and fertilization during the restoration of semiarid motorway slopes.** *Ecol Eng* 2010, **36**:1290–1298.



27. Jakobsson S, Bernes C, Bullock JM, Verheyen K, Lindborg R: **How does roadside vegetation management affect the diversity of vascular plants and invertebrates? A systematic review.** *Environ Evid* 2018, **7**:1–14.
28. Wang M, Liu Q, Pang X: **Evaluating ecological effects of roadside slope restoration techniques: a global meta-analysis.** *J Environ Manag* 2021, **281**, 111867.
- This is a comprehensive global synthesis of the state-of-the-art of roadside slope restoration and the evaluation of the various available techniques.
29. Mola I, Jiménez MD, López-Jiménez N, Casado MA, Balaguer L: **Roadside reclamation outside the revegetation season: management options under schedule pressure.** *Restor Ecol* 2011, **19**:83–92.
30. Mehlhoop AC, Skringo AB, Evju M, Hagen D: **Best practice – is natural revegetation sufficient to achieve mitigation goals in road construction?** *Appl Veg Sci* 2022, **25**, e12673.
- This study evaluates the effectiveness of roadside restoration in Norway and helps to design realistic restoration targets.
31. Bochet E, Tormo J, García-Fayos P: **Native species for road-slope revegetation: selection, validation, and cost effectiveness.** *Restor Ecol* 2010, **18**:656–663.
32. Mallik AU, Karim MN: **Roadside revegetation with native plants: experimental seeding and transplanting of stem cuttings.** *Appl Veg Sci* 2008, **11**:547–554.
33. Ladouceur E, Jiménez-Alfaro B, Marin M, De Vitis M, Abbandonato H, Iannetta PP, Bonomi C, Pritchard HW: **Native seed supply and the restoration species pool.** *Conserv Lett* 2018, **11**, e12381.
34. Borza S, Godó L, Valkó O, Végvári Z, Deák B: **Better safe than sorry – understanding the attitude and habits of drivers can help mitigating animal-vehicle collisions.** *J Environ Manag* 2023, **339**, 117917.
35. Song G, Li Z, Yang Y, Semakula HM, Zhang S: **Assessment of ecological vulnerability and decision-making application for prioritizing roadside ecological restoration: a method combining geographic information system, Delphi survey and Monte Carlo simulation.** *Ecol Indic* 2015, **52**:57–65.
36. Plue J, Kimberley A, Bullock JM, Hellemans B, Hooftman DA, Krickl P, Leus L, Peeters G, Poschlod P, Traveset A, *et al.*: **Green infrastructure can promote plant functional connectivity in a grassland species around fragmented semi-natural grasslands in NW-Europe.** *Ecography* 2022, **2022**, e06290.
- This large-scale study demonstrates the importance of the green infrastructure along roads in maintaining the genetic diversity of grassland species.
37. New TR, Sands DP, Taylor GS: **Roles of roadside vegetation in insect conservation in Australia.** *Aust Entomol* 2021, **60**: 128–137.
38. von Königsłow V, Mupepele AC, Klein AM, jewels Overlooked: **Existing habitat patches complement sown flower strips to conserve pollinators.** *Biol Conserv* 2021, **261**, 109263.
39. Nemeček K, Stephenson A, Gonzalez EA, Losch M: **Local decision-makers' perspectives on roadside revegetation and management in Iowa, USA.** *Environ Manag* 2021, **67**: 1060–1074.
40. Fernandes GW, Banhos A, Barbosa NPU, Barbosa M, Bergallo HG, Loureiro CG, Overbeck GE, Solar R, Strassburg BBN, Vale MM: **Restoring Brazil's road margins could help the country offset its CO2 emissions and comply with the Bonn and Paris Agreements.** *Perspect Ecol Conserv* 2018, **16**:105–112.
41. Pedrini S, Gibson-Roy P, Trivedi C, Gálvez-Ramírez C, Hardwick K, Shaw N, Frischie S, Laverack G, Dixon K: **Collection and production of native seeds for ecological restoration.** *Restor Ecol* 2020, **28**:S228–S238.
42. Pedrini S, Balestrazzi A, Madsen MD, Bhalsing K, Hardegree SP, Dixon KW, Kildisheva OA: **Seed enhancement: getting seeds restoration-ready.** *Restor Ecol* 2020, **28**:S266–S275.
43. Steidle JL, Kimmich T, Csader M, Betz O: **Negative impact of roadside mowing on arthropod fauna and its reduction with 'arthropod-friendly' mowing technique.** *J Appl Entomol* 2022, **146**:465–472.
44. Knight SM, Norris DR, Derbyshire R, Flockhart DT: **Strategic mowing of roadside milkweeds increases monarch butterfly oviposition.** *Global Ecol Conserv* 2019, **19**, e00678.
45. Haan NL, Hunter MR, Hunter MD: **Investigating predictors of plant establishment during roadside restoration.** *Restor Ecol* 2012, **20**:315–321.
46. Bochet E, García-Fayos P: **Identifying plant traits: a key aspect for species selection in restoration of eroded roadsides in semiarid environments.** *Ecol Eng* 2015, **83**:444–451.
47. Stokes A, Douglas GB, Fourcaud T, Giadrossich F, Gillies C, Hubble T, Kim JH, Loades KW, Mao Z, McIvor IR, *et al.*: **Ecological mitigation of hillslope instability: ten key issues facing researchers and practitioners.** *Plant Soil* 2014, **377**: 1–23.
48. Park S, Kim JH, Byun C, Hong SY, Lee EJ: **Identification of restoration species for early roadcut slope regeneration using functional group approach.** *Restor Ecol* 2021, **29**, e13424.
49. Son D, Alday JG, Chu Y, Lee EJ, Park S, Lee H: **Plant species colonization in newly created road habitats of South Korea: insights for more effective restoration.** *Sci Total Environ* 2020, **719**, 137476.
50. Janečková P, Řehounková K, Vítovcová K, Šebelíková L, Prach K: **Spontaneous succession on road verges – an effective approach with minimum effort.** *Land Degrad Dev* 2021, **32**:2726–2734.
- In this large-scale study the authors surveyed the vegetation of road-side verges across the Czech Republic and showed that spontaneous recovery is a promising option for roadside restoration that should be given higher priority.
51. Soper JM, Raynor EJ, Wienhold C, Schacht WH: **Evaluating composition and conservation value of roadside plant communities in a grassland biome.** *Environ Manag* 2019, **63**: 789–803.

According to the Author Guidelines: 'The majority of the references (please aim to cite approximately 50) should come from the period under review (i.e. the past two years) and, in general, at least 10% of these should be selected and annotated as being papers of special interest (\*) or outstanding interest (\*\*). Annotated references MUST be from the past two years, and the annotation should provide a brief description of the major findings and the importance of the study.'