CEDR Transnational Road Research Programme
Call 2016: Biodiversity

funded by Austria, Germany, Ireland, Netherlands, Norway, Slovenia, and Sweden

Conférence Européenne des Directeurs des Routes
Conference of European Directors of Roads

EPICroads – Ecology in practice: Improving infrastructure habitats along roads

Practical Guidelines *Ecology in practice: Improving infrastructure habitats along roads*

Deliverables No 2.3–2.5
10, 2021

CEDR Call 2016: Biodiversity
EPICroads

Ecology in practice: Improving infrastructure habitats along roads

Practical Guidelines *Ecology in practice: Improving infrastructure habitats along roads*

Planned delivery date: 04/30/2020
Actual delivery date: 29/10/2021

Start date of project: 01/05/2018

Authors of this deliverable:

Hans Martin Hanslin, Svenja B. Kroeger, Giulia Bastianelli: Norwegian Institute of Bioeconomy Research (NIBIO), Norway

Tommy Lennartsson, Weronika Axelsson Linkowski, Jörgen Wissman, Anna Westin: Swedish Biodiversity Centre, SLU, Sweden

Marcello D'Amico: CIBIO-InBIO, University of Porto and University of Lisbon, Portugal

Christina Fischer: University of Salzburg, Austria and Anhalt University of Applied Sciences, Germany

Johannes Kollmann: NIBIO and Technical University of Munich, Germany

Main responsibilities: Hanslin – general part, D'Amico – landscape part, Kollmann – ecotone part, Lennartsson – habitat part

PEB Project contact: Pia Bartels and Anders Sjölund

Version 29.10.2021

Table of contents

Executive summary

This document contains guidelines on how ecological principles can be fully incorporated in the different phases from planning, to preparation and decision to implementation. These aspects are addressed with a landscape, ecotone, and habitat perspective. The document contains a general introduction on roadside challenges and concepts, the ecological principles underpinning the approach, and guidelines from a landscape perspective, to edge and ecotone effects, to roadside habitat quality. The specific guidelines are based on comprehensive reviews of the scientific and grey literature in the project *Ecology in practice: Improving infrastructure habitats along roads* (EPICroads). With a European perspective, the guidelines target an audience of strategic and operational planners at road authorities.

The research draws attention to the contrasts between road impact at local (roadside) and landscape scales. Road impact at the local scale is a combination of direct habitat loss, edge and ecotone effects, and the ecological quality of roadsides. In a landscape context, road networks affect abiotic (e.g., groundwater flows) and biotic (dispersal and migration) connections, and increase edge density, accumulate road impact zones and potentially increase habitat diversity. To help addressing this spatio-temporal complexity in road projects, we use three concepts: (i) How roads impact biodiversity in the wider landscape? (ii) How the roadside connects to the adjacent landscape through a series of transition zones ('roadside ecotone')? And (iii) how habitat quality differs among roadsides? In each guideline, we present key results from the conducted reviews, how we interpret these findings, and how they can be applied in practice.

The landscape part comprises a stepwise procedure to identify the most suitable approach for building and managing roadsides that host high biodiversity. Guidelines are provided for each landscape type, based on a literature review of seven major road impacts (road-kills, habitat fragmentation, biological invasions, light pollution, noise pollution, chemical pollution and hydrogeological alterations). Two practical examples of using the landscape guidelines are provided in an annex. In the ecotone guidelines, we address how gradients along and across the roadside contribute structures and resources for biodiversity, and how they relate to habitat quality and landscape processes and configuration. Strategies to avoid ecological trap effects through clever design of the roadside habitats are addressed in these guidelines. The habitat guidelines address measures to improve the basis for biodiversity in roadsides, with a strong focus on the importance of management. The guidelines help identifying road sections with high potential biodiversity and provide approaches for prioritisation based on both local and landscape context. This includes the importance of historical legacy and conservation concerns.

Overall, the guidelines indicate that the quality of roadside habitats and their contributions to ecological processes and biodiversity, at three scales, can clearly be improved through targeted actions in roadside planning, construction and management. The guidelines also identify the landscape perspective as essential for measures at local scales. Trade-offs between expected outcomes of measures, such

as potential ecological trap effects or management of invasive species need to be addressed. The guidelines provide a general framework that should be translated into local contexts with the respective recommendations. Moreover, although the guidelines are based on a large volume of literature, there are several knowledge gaps to be filled in new projects. Some of these are pointed out in the guidelines and the supporting reports.

1 Ecological challenges in road projects

There is currently a global biodiversity crisis due to land-use change, eutrophication, fragmentation, invasive alien species and climate change (IPBES 2019). Road projects interact with all of these drivers, affecting ecological processes at both local and larger spatial scales. In the guidelines laid out in this document, the critical components are (i) local habitat quality, (ii) processes at transition zones (ecotones) between roads and other land use areas, as well as (iii) processes in the wider landscape (Box 1). These guidelines do not replace an ecological impact assessment but provide additional information on how to mitigate the negative impact of roads on biodiversity and ecosystem services.

1.1 Impacts at a local scale

Road impacts at local scales are a combination of direct loss of habitat, edge effects and the ecological quality of roadsides. Edge effects of roads can have considerable impacts on organisms through changes in abiotic conditions, such as shade, temperature, wind, soil humidity and hydrology. In addition, edge habitats face increased exposure to traffic noise, artificial light, and pollution. These spatially correlated factors define the road impact zone (Biglin & Dupigny-Giroux 2006), they decline with distance from the road, and are highly affected by landscape configuration (Figure 1.2). A simple approach to model road impact zones is presented by Shilling and Waetjen (2012). Biotic interactions are also affected along these edges. Roadsides act as corridors for dispersal of invasive plant species and contribute to floristic homogenisation along roads including dispersal to surrounding areas. Road-kill and technical infrastructure provide generalist predators and scavengers with resources and access to larger areas, which affects local population dynamics of other species.

In highly altered landscapes, roads may have positive effects on biodiversity by providing replacement habitats and refuges for species that have lost their natural habitats due to urbanisation, intensive agriculture, or forestry. In many cases, roadsides represent novel habitats based on new combinations of species composition, management, and other disturbances. In such landscapes, the roadside contributions to ecosystem services are significant, and the importance is predicted to increase (Philips et al 2020).

Box 1: Spatial and ecological scales addressed in the guidelines

Roadside habitat – Areas of the roadside directly affected by road construction and management, characterized primarily by physio-chemical features and vegetation structure, and providing resources for many species.

Ecotone – The transition zone from one habitat type to another. For roadsides this is the transition from short usually grass dominated vegetation close to the road, to other vegetation types further away from the road, be it shrubland, agricultural land or forests. This transition may be sharp or gradual, and is often set by differences in management, such as cutting regimes. As two or more habitats meet in ecotones, they provide ample opportunities for many organisms and are often species-rich.

Landscape – The large-scale area surrounding the road corridor that influence ecological processes at the roadside. The extent of the 'ecological landscape' differs among species depending on their home ranges and dispersal, typically to a distance of a few hundred meters to a few kilometres from the road.

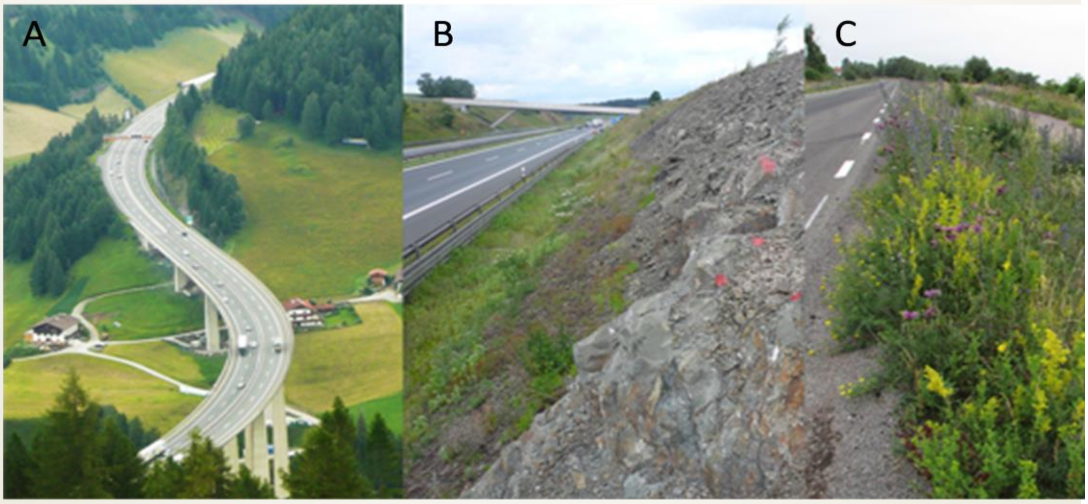


Figure 1.1: Examples for the three scales used by the EPICroads Guidelines. (A) High-montane ***landscape*** at the Brenner motorway with an effective habitat corridor (Steinach, Tyrol, Austria; July 2009), (B) well-designed ***ecotone*** with contrasting site conditions on diabase bedrock along and across a low-montane motorway (Hof, NE Bavaria, Germany; June 2012), and (C) a species-rich ***habitat*** on calcareous soil is created by ground disturbance between a road and bicycle path and maintained by late cutting (Byxelkrok, Öland, Sweden; July 2011).

1.2 Impacts at a larger scale

Landscape fragmentation by road networks has a considerable impact on biodiversity and ecological processes worldwide (EEA-FOEN 2/2011 *Landscape fragmentation in Europe*). Road networks increase edge density in the landscape and cumulate road impact zones. Therefore, habitat loss through road building is much larger than the land lost through construction alone (Forman & Alexander 1998). The consequences are reduced total area and patch size of high-quality habitats, restricted movement and gene flow between remaining patches, and direct negative effects on wildlife through road-kills. It comes as no surprise that such changes have consequences for biodiversity, although many effects are difficult to detect in the short-term. Delayed responses in population decline after the reduction in habitat quality and area can be described as an ‘extinction debt’ within the local species pool (Figueiredo et al. 2019). This means that effects of road projects on biodiversity may not be detected until decades later. Specialist species are vulnerable to these processes, but many previously common species also show sharp declines over time.

Although the impact of single roads increases in scale with increasing traffic volume and speed, the impact of smaller roads is still significant. Hence, accumulated effects at the scale of road networks must be addressed and estimated, including other features acting as barriers, such as railroads and fences, using “Infrastructural landscape fragmentation” or similar metrics (Ledda and De Montis 2019).

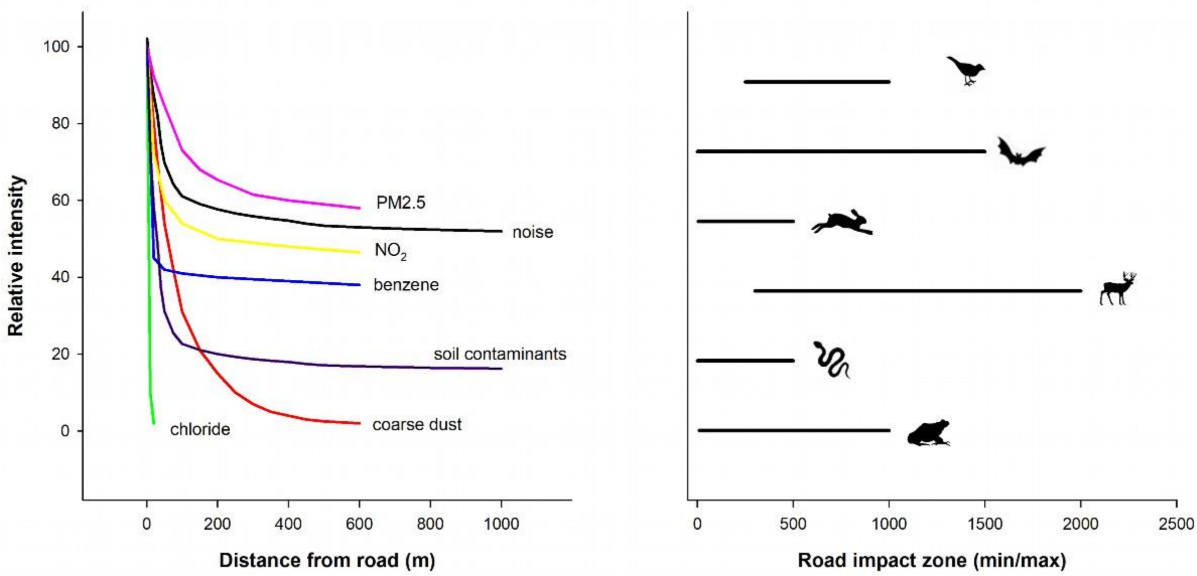


Figure 1.2. Examples of decline in intensity of selected contaminants and disturbances with distance away from the road (left) and typical minimum and maximum road impact zones for different organism groups (right, in meter). Collated from references in Hanslin et al. (2019). Note that these trajectories and road impact zones differ considerably with landscape configuration and that road impact zones are highly species-specific.

At the landscape scale, habitats along roads may function as corridors for dispersal of genes and individuals of a wide range of organisms, i.e., a function that reduces biodiversity loss. Given proper construction and maintenance, this potential to reconnect remaining habitat patches can be addressed within road projects. A central challenge is how to provide habitat and corridor functions for native organisms, without promoting invasive species and unintended biotic interactions. These aspects are addressed by the guidelines.

Box 2: Focal species

The taxonomic focus of these guidelines is wide, but with a weight on species that complete most, or at least critical parts, of their life cycle within roadside habitats. Such species are mainly plants, invertebrates, and small vertebrates, such as amphibians, reptiles, and small mammals. Larger mammals are generally not included, as road impacts on these are addressed in other CEDR projects. Larger mammals, however, are mentioned in the landscape guidelines, as they often are involved in relevant road impacts for certain landscape types. In those cases, the guidelines suggest how to mitigate such impacts for larger vertebrates while increasing roadside presence and abundance of target species (i.e., plants, invertebrates, and small vertebrates). Based on a particularly large volume of literature on plants and insects, compared to other organisms, much of our guidelines are based on these taxonomic groups.

2 Background on planning roadside habitats for biodiversity

Sound integration of ecological knowledge into road projects requires challenges to be addressed early in the strategic planning and continuously throughout the road project (Roberts & Sjölund 2015). It is also crucial to have a landscape perspective and to include indirect and cumulative effects when assessing potential impacts of the road project itself, the road network and planned development.

Required background information to provide a reasonable ecological assessment of road projects includes:

- Standard mapped data for the landscape (topology, hydrology, precipitation, wind, bedrock, soil type, land use, vegetation).
- Ecological investigations with desktop analyses and field surveys identifying critical habitats, existing corridors, ecosystems, and species of conservation concern, both along the road transect and in the larger landscape.
- Protected natural areas at local, federal, state, or international levels (Natura 2000 sites).
- Detailed road (and transport) network maps and their projected zones of ecological impact.
- An analysis of recent historical changes of land use within the study landscape.

- Planned and expected urban and transport development, including effects of the new or rebuilt road on urban development along the road.

The planning process must build on formalised approaches with strategic environmental assessments (SEA) and environmental impact assessments (EIA), where the landscape perspective and cumulative effects are addressed with sufficient detail and quality (Broniewicz & Ogrodnik 2020). This can reduce negative impacts and realise potential positive contributions. Uncertainty and risks associated with selected strategies should be acknowledged and a high level of caution applied where areas of high quality or high conservation value are at risk. The guidelines are to be read as supplements to the SEA and EIA.

The specific recommendations can assist in planning road projects including the most important environmental gradients. However, there will always be a need for adjustments to the actual conditions due to local, regional, or national differences in terrain, bedrock, landscape, climate, and legislation.

3 Knowledge platforms for development of guidelines

To develop guidelines, we followed some basic ecological principles as expressed in the principles and standards of the Society for Ecological Restoration (Gann *et al*. 2019):

1. Characteristic species composition
2. Suppression of invasive alien species
3. Establishment of functional species groups
4. Reproduction of target species
5. Normal ecosystem functions
6. Integration within the landscape
7. No negative external influences
8. Resilient to stress and disturbance
9. Sustainable ecosystems in a dynamic sense

Perhaps the most important principle is to not introduce new systems in the landscape, but to support and develop existing or historical structures and local biodiversity (for example, not to introduce a calcareous roadside in an acidic landscape).

We based the guidelines on a set of reviews and reports developed within the CEDR-funded EPICroads project, for which we extracted relevant information for planning, design, construction, and management of roads from the scientific literature. The reports are intended to function as in-depth reading on the respective topics. Grey literature sources were also checked, but usually too site-specific or methodologically inadequate to act as a base for comprehensive guidelines.

The reviews of factors controlling roadside biodiversity presented conclusions on a wide range of topics and with a high level of detail. Different conclusions are relevant for different functions in road administration, from strategic planning and capacity building to planning, project management and design of construction and rebuilding projects and maintenance. The guidelines are structured based on three major aspects: (i) habitat qualities, (ii) ecotone and ecological traps, and (iii) landscape perspectives, with the most critical parts in each of these addressed in separate guidelines. Guideline contents include key results from the reviews, interpretation of these results, implications for different parts of road projects and recommendations in the form of short guidelines.

Although there are many published studies on road ecology, there are also many and considerable knowledge gaps in understanding road impacts and in efficiency of mitigation measures. These gaps are addressed by our respective reports (Hanslin *et al*. 2019, Lennartsson *et al*. 2021).

4 Introduction to guidelines

4.1 *Themes and challenges*

As stated above, the guidelines are structured into three themes, i.e., landscape, ecotone, and habitat, which correspond to the spatial scales addressed (Box 1). Table 4.1 provides a summary of the main environmental challenges addressed in the respective guideline themes, and Box 2 outlines the focal species of the guidelines.

Most challenges are addressed by two or more guidelines, albeit from different perspectives. Hence, to obtain information on a given environmental challenge, more than one guideline theme must be considered. A graphical approach to the use of the guidelines in road construction and maintenance is presented in Box 3.

Table 4.1: Summary of EPICroads guidelines with respect to the main environmental challenges during planning, construction, and management of roadsides. The significance of the challenge depends on the spatio-temporal scale considered within four levels: weak (white), moderate (grey), strong (dark-grey).

Environmental challenges	**Spatio-temporal scale of roadside management**		
	Landscape	Ecotone	Habitat
1 Limited width of road corridor			
2 Extreme (lateral) road profile			
3 Erosion and slope instability			
4 Drought or flooding			
5 Pollution (salt, heavy metals, light)			
6 Eutrophication			
7 Unsuitable soil microbiomes			
8 Poor (or unsuitable) seed bank			
9 Dispersal limitation			

10 Road-kill			
11 Invasive alien species			
12 Native dominant species			
13 Traps for rare species			

Box 3: How to use the guidelines

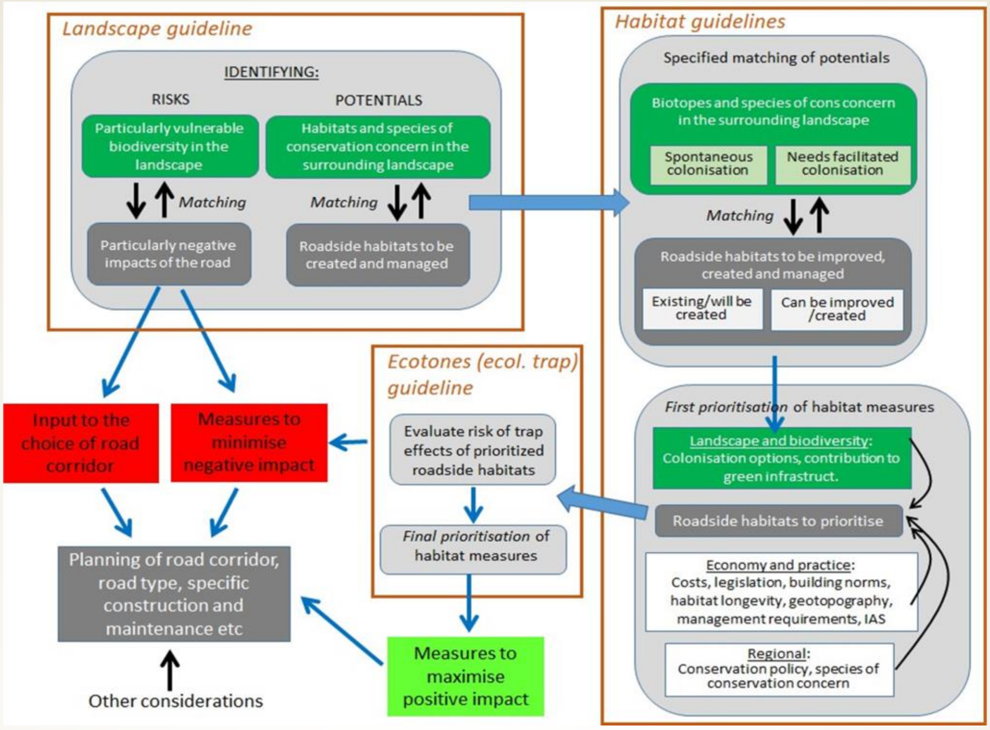


Figure 4.2: Suggested use of the EPICroads guidelines during road construction and maintenance, where the *Landscape guideline* sets the stage and is supported by the *Habitat* and *Ecotone guidelines*, together providing a framework for assessing risks and exploring benefits in road projects.

1. The ***Landscape guidelines*** are used to identify how a road may produce risks and potentials for biodiversity at the landscape level. Risks are identified by investigating matches between critical road features and vulnerable biodiversity. Identified risks must be considered when a corridor for a new road is planned, and measures to minimise negative impacts of new and existing roads should be suggested. The potential to support biodiversity is identified by investigating matches between ecologically valuable road features and potentially favoured biodiversity at the landscape scale.

2. The identified potential for biodiversity of conservation concern is elaborated in the ***Habitat guidelines***, where specific matches between potential roadside habitats and biodiversity are investigated. Both roadside species present and potential coloniser species are considered. Measures to favour biodiversity may be introduced when building or rebuilding roads, and in ongoing maintenance. Positive roadside–biodiversity matches indicate particularly important roadside habitats. The prioritisation of habitats to create and to maintain is also influenced by economic, practical and regional factors.

3. Before creating and maintaining habitats potential trap effects should be evaluated using the ***Ecotone guidelines***. Identified risks of trap effects should influence the final choice of roadside habitats and suggest further measures to minimise negative effects of the road on biodiversity. The final choice of which roadside habitats to create and maintain (e.g., by vegetation management) constitutes a recommendation for how to utilise the potential of a road to favour biodiversity.

4.2 Guidelines – step by step

Here we provide a short overview of the key points in the guidelines with indications on where to find the detailed descriptions by reference to the chapters and subchapters. This is a more in-depth description of the information in Box 3. This step-by-step list is primarily for new road projects, but elements can be applied in the renovation and management of existing roads.

Initial work
Collect and map information and data on bedrock, soils, protected and other species, habitats, and areas of conservation concern from databases and species and habitat inventories, weather, and climate (➔ **2**).

Extract key points from the EIA concerning environmental risks.

Landscape constraints and potential
Identify landscape **constraints** based on climate, geomorphology, or land use (➔ **5.2**), including

- The need for erosion control
- The occurrence of invasive species in need of targeted management
- Noise, light, and contaminant gradients

Investigate how the road corridor contributes to landscape fragmentation alone and in the larger network of roads, rails, and other linear infrastructure (➔ **1.2 and Box 5**)

- Delineate road impact zones on topographic maps to identify conflict areas.
- Analyse how and where the road corridor will interrupt structural connectivity in the landscape (for important habitats and landscape elements).

Identify the type and **potential for biodiversity** in the landscape based on species pools (including invasive species) and mapped biotopes/habitats (➔ **7.4**) considering:

- Remnants of historical land use with high biodiversity, such as semi-natural meadows and pastures.
- Occurrences of species of conservation concern, especially belonging to open and other habitats comparable to roadside habitats.
- Decide if there are habitats that should be given priority along the road, typically roadside habitat types that may resemble or support species from habitats that are in decline in the surrounding landscape, to increase the total habitat area or landscape connectivity, or to function as replacement habitats.
- Assess potentials for spontaneous colonisation of target species (e.g., species of conservation concern), and consider seeding/planting where chances are low.

Identify the need for and **potential for increased connectivity** in the landscape based on resistance to movement in contrasting land-use types and the spatial isolation of key elements (➔ **Box 5**).

- Urbanised areas and large areas of cropland or forest have high resistance to movement for many open-land organisms, while meadows, patchy landscapes and edges have less resistance, and open land usually has a high resistance to movements of forest organisms.

- Identify stretches that can provide connectivity along the road by 1) identify stretches that geographically connects habitat patches in the landscape; 2) assess the potential to create valuable roadside habitats in these stretches (➔**7.2**); 3) prioritise stretches that have high values regarding both 1) and 2); and make the prioritised stretches as beneficial as possible for biodiversity (➔**7.2**), including measures for minimising risk of ecological traps ➔ (**6.3**).

Analyse the occurrence and diaspore pressure of invasive alien species in the landscape, to prioritise areas with low pressure for biodiversity initiatives (➔ **5.2/7.2**)

- Take action to stop establishment of invasive species before, during and after road construction.
- Do not promote connectivity when there is a risk of introducing invasive species to valuable and/or protected areas, both in roadside environments and in the surrounding landscape.

Ecotones – transition zones

Design and maintain transition zones between systems (ecotones) to connect the roadside to the larger landscape (➔ **6.2**).

- Design shelterbelts and forest edges to reduce noise, pollution, and light dispersion, while providing habitats and resources.
- Explore the variation in environmental conditions (humidity, soil characteristics, shade) and management strategies along the road to design and maintain transition zones.

Reduce the risk of trap effects by placing resources away from the road and prioritise wider and steeper roadsides for biodiversity measures, avoiding such approaches in narrow roadsides and situations with potentially high turbulence **(➔ 6.3**).

Habitat quality

Map and prioritise stretches for potentially high-quality habitats based on their size, terrain and shape, and information on the landscape potential (➔ **7.2**).

- Higher and wider roadsides are more valuable because they increase habitat area and can reduce the risk of traffic mortality.
- Longer stretches of habitat are more valuable because of larger habitat area and increased potential for dispersal along the road; a patchwork of several smaller habitat patches situated a maximum of a few hundred metres apart may be as beneficial as one larger habitat area.
- Sun-exposed surfaces favour biodiversity in colder and more humid regions, while the opposite may hold in dry and warm regions.

Map and prioritise stretches for potentially high ecological quality based on soil and bedrock properties. Low-productivity (nutrient-poor and well-drained) soils have in general the best potential for forming biodiversity-rich habitats that support communities with low productivity that slow down succession and prevent the dominance of tall growing species (➔ **7.2**).

- Map roadside potential for high quality habitats by combining information on topography, exposure, and soil characteristics.
- Identify cut slopes of native nutrient-poor and well-drained soils not to be covered by topsoil.
- Develop a soil management plan that ensure reuse of native soil qualities for targeted purposes based on the roadside potential.
- Re-use local topsoil only when it can contribute to a low-productivity habitat with no seedbank or fragments of invasive species.
- Check if habitats and vegetations based on other soil types (e.g., calcareous) would be important for the respective project.

For the establishment of desired plant species in roadsides, it is often not possible to rely entirely on spontaneous colonisation from surrounding habitats, and thus establishment has to be facilitated by active transfer of seeds, hay or plants (➔ **7.2**).

- Source seed or plant material early in the project, if active vegetation establishment is required, prioritizing local origin.
- Allow slow establishment and succession instead of aiming at rapidly establishing a dense vegetation cover.
- Avoid competitive grasses and high-density grass seeding unless erosion prevention calls for a denser vegetation cover.

Develop a management plan for the roadside habitats **(➔ 7.3/7.4**)

- Develop objectives for ecological functions and structures for defined stretches of the road.
- Tune cutting regime (timing and frequency) to the productivity and phenology of the vegetation.
- Identify stretches where removal of the cut material would be beneficial and find solutions to remove the cut material.
- Plan for needs of surface disturbance during maintenance in order to reset succession.
- Provide specific management instructions for transition zone.

Develop a monitoring program for adaptive management, knowledge development and evaluation (➔ **6.2/7.2**)

- Target indicators to represent relevant metrics of biodiversity and ecological functions related to your objectives (for example occurrence of habitat specific species and occurrence of invasive species).
- Document and report results to contribute to the knowledge base on road ecology.
- Develop approaches for internal capacity building, including targeted applied research projects and knowledge syntheses.

5 Landscape guidelines

Summary

- The *Landscape guidelines* represent the first step for planning and managing roadsides hosting high biodiversity and should always be used together with the *Ecotone* and *Habitat guidelines*.
- The *Landscape guidelines* are based on 126 literature reviews on seven major road impacts on plants, invertebrates, and small vertebrates (road-kills, habitat loss and fragmentation, biological invasions, light pollution, noise pollution, chemical pollution, and hydrogeological alterations) in 18 landscape types.
- The 18 considered landscape types are presented in landscape dichotomies concerning their features: climate (qarm vs. cold landscapes, snowy/frosty vs. snowless/frostless landscapes, and humid vs. arid landscapes), geomorphology (mountains vs. flatlands, wetlands vs. drylands, coastal vs. inland landscapes), and land use (forests vs. open lands, extensive vs. intensive landscapes, homogeneous vs. heterogeneous landscapes).

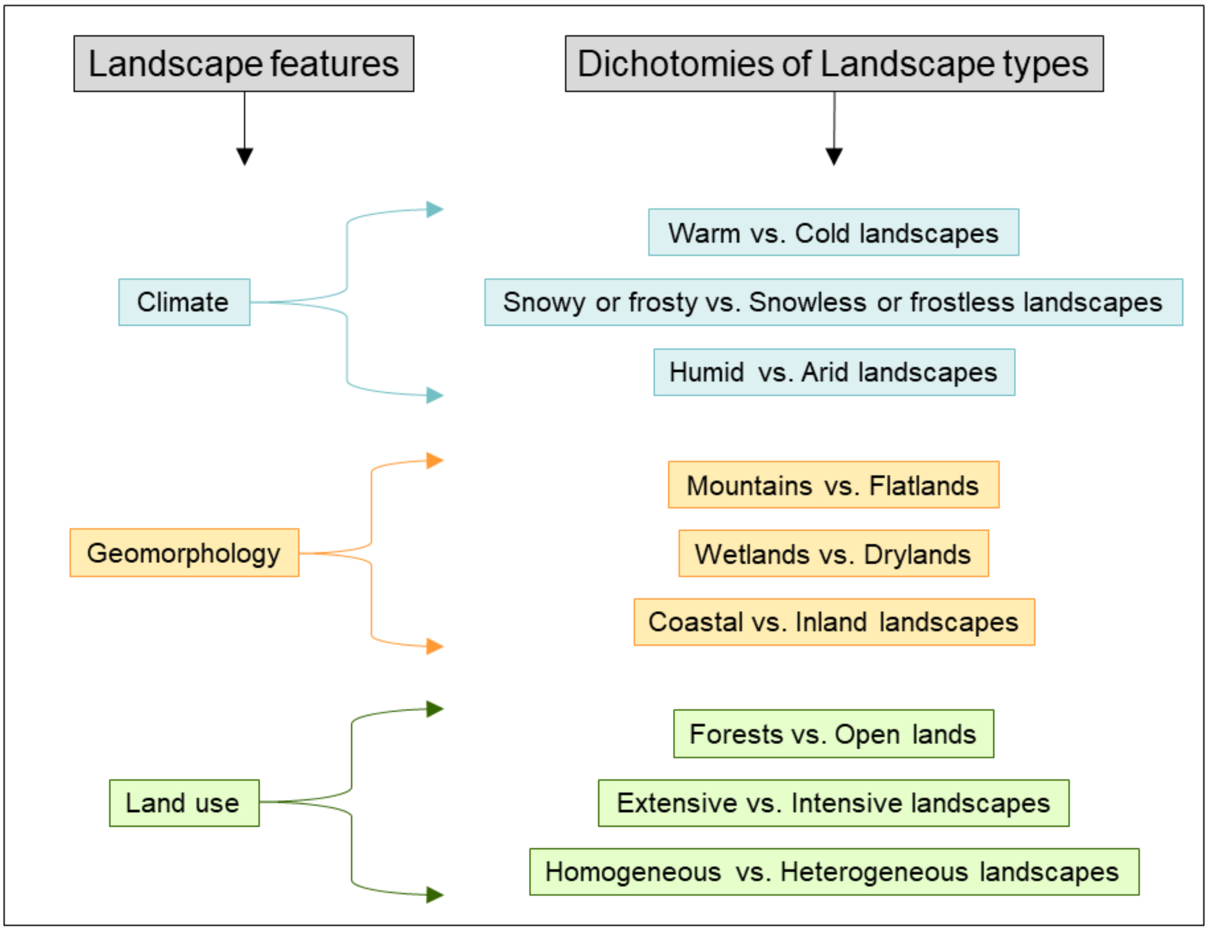
5.1 Introduction

5.1.1 Approach

Construction and management of roadsides with the aim of hosting high biodiversity and multiple ecosystem functions has to consider the matrix landscape within which roads are embedded. Landscapes are ecological systems that exist at a scale of kilometres with distinct climatic, geomorphological, and land-use characteristics. We define 'landscape guidelines' as a series of practical instructions, based on the latest scientific and technical literature on large-scale effects in roadside habitats. This part of the report provides a list of topics focused on the most important large-scale impacts and landscape types, as well as a stepwise procedure aiming to help road planners in selecting the most suitable recommendations for building and managing roadsides in the respective target areas. Importantly, the landscape guidelines provided here represent only a first step for determining how to act in a given target area. The subsequent steps must consult the *Ecotone* and *Habitat guidelines*, always taking local factors into account.

The first section of this chapter (*5.1 Introduction*) is an outline of the implemented approach, including criteria to create the landscape guidelines. The second section (*5.2 Landscape types, related impacts, and guidelines*) is a description of the specific features that constitute the considered landscape types. For example, geomorphological characteristics (such as orography) will the classification of landscapes as mountainous or flatland. Each established landscape feature in turn includes three dichotomies of landscape types (Figure 5.1). In the beginning of this section, there is a sub-section including general guidelines that can be applied to most landscape types.

Figure 5.1: Dichotomies of landscape types for three landscape features. Definitions of landscape types are provided below, in the corresponding sections.



The second section of this chapter is based on seven literature reviews performed for each landscape type, each one focusing on a major road impact (i.e. road-kills, habitat loss and fragmentation, biological invasions, light pollution, noise pollution, chemical pollution and hydrogeological alterations). As a consequence, 126 literature reviews have been performed, each one focusing on a given major road impact in a given landscape type (i.e. starting from road-kills in warm landscapes, considering all the possible combinations, and ending with hydrogeological alterations in heterogeneous landscapes). The aim of such reviews was determining the relevance of the considered road impacts in each landscape type, and ultimately understanding whether such impacts can be mitigated while building and managing roadsides that host high biodiversity. For each landscape dichotomy, the second section of this chapter provides key results from the corresponding reviews, their interpretation, and several guidelines focusing on improved building and management of roadsides that host high biodiversity while limiting negative road impacts. Importantly, guidelines are not provided for those landscape types in which some road impacts may be relevant but cannot be mitigated by roadside building or management. For example, all landscape types can suffer high road-kill rates, but only in some landscapes road-kill impact can be mitigated by suitable roadside building or management.

The third section of this chapter explains the stepwise procedure involved in selecting the most suitable landscape guidelines for building and managing roadsides hosting high biodiversity in a given target area of Europe (see Annex 2 for explicit examples).

This stepwise procedure is based on landscape dichotomies because this is a user-friendly approach that will help road planners to select the guidelines concerning their target area. However, the intrinsic mechanism of dichotomies implies that there will be study areas that cannot be assigned to any landscape type. For example, a hilly landscape cannot be listed as mountains or flatlands. Nevertheless, using the stepwise procedure, road planners will be able to assign their study areas to other landscape types (the aforementioned hilly landscape, for example, might be a warm, snowless, arid landscape, and so on), obtaining in any case a relevant amount of landscape guidelines that will be implemented together with the *Ecotone* and *Habitat guidelines*.

5.1.2 Criteria

The *Landscape guidelines* focus primarily on plants, invertebrates and small vertebrates (Box 2). Along with the landscape guidelines, there are also suggestions on how to facilitate the presence of species of conservation-concern at roadsides. These suggestions may not always be applicable for some of these species, especially for legal issues related to red-listed species. However, some of these species only persist in roadside habitats, and in those cases, they should be preserved and their connectivity to the natural habitat should be prioritised. Conversely, species of conservation-concern is a wider concept than legally protected or red-listed species, which can include locally (but not globally) threatened, endangered or declining populations of relatively common species, or least-concern species that support threatened species.

As a consequence of the above-mentioned criteria, implementation of these landscape guidelines in a given target area should be based on suitable and recent knowledge of the local context, such as species inventories, conservation priorities and local threats. As an example of local threats, please see the Box 4 on Traffic volume for more details.

5.2 Landscape types, related impacts and guidelines

5.2.1 General landscape guidelines

Some guidelines are relevant across most landscapes, and are presented here.
These come in addition to the guidelines for specific landscapes elaborated in 5.2.2

Measures to prevent road-kills

Road fences can be established to reduce road-kills (especially for ungulates in snowy or frosty landscapes, and for all vertebrates along downhill roadsides of mountains and inland roadsides of coastal roads), but always in correspondence with natural wildlife corridors and combined with suitable wildlife road-crossing structures.

Road-kill risk can be reduced by increasing visibility between wildlife and drivers through establishment of low vegetation at roadsides (especially in humid landscapes and forests); here native shortgrass species should be prioritised.

Measures to reduce habitat fragmentation

Fragmented populations (especially plants, but also animals) can be connected by establishing corridor and stepping-stone habitats at roadsides to allow dispersal of genes and individuals along roads (Box 5) and by wildlife-crossing structures to promote dispersal across roads. For high-priority species, a thorough understanding of the differences between structural connectivity that can be manipulated in road projects and the species-specific functional connectivity is required. This will have consequences for corridor characteristics and stepping stone configuration (size, quality and distances). A rough estimate of distances between stepping stone patches to allow for within generation dispersal is a few hundred meters for small (and less mobile) arthropods, while larger flying insects, reptiles and small mammals, can extend much further (to kilometres). This is however highly dependent on the quality of the matrix between the habitat patches and differences in life-history and foraging strategies between species. The higher the quality of the area between high quality patces, the better facilitation of movement and dispersal.

To facilitate dispersal across generations (especially important for short-lived species), the size and quality of the individual patches have to provide for completion of a life cycle. It is, however, important not to overestimate the spatial range of corridor and stepping stone functions (within generation) when roadsides themselves do not function as (high-quality) habitats. See box 5 for details.

In low-traffic scenarios, conservation-concern species can be established, whereas in high-traffic scenarios common native species should be used, preferably providing ecosystem services and potentially unaffected by ecological traps. This guideline is especially suitable for mountains, wetlands (using roadside ponds), coastal landscapes, both natural forests (using hedgerows and tree rows) and open lands, and heterogeneous landscapes.

Measures to control biological invasions

Early detection and rapid response (EDRR hereafter) to biological invasions is recommended for warm landscapes, flatlands, wetlands, coastal landscapes, open lands, intensive landscapes and homogeneous landscapes, especially under high-traffic scenarios. Importantly, this includes measures before and during the construction or renovation phase, targeting source populations in the landscape and proper soil management.

Measures to limit light pollution

Street lamps should not be installed (where possible), especially in wetlands and coastal landscapes, and the impact should be mitigated by choosing less-impacting light sources (e.g. sodium lamps), directional lights focused on the road, and timed or intelligent (with movement sensors) road lighting.

The negative effects of street lamps and headlights in high-traffic scenarios should be mitigated by establishing shelterbelts of native trees and shrubs (along mountain roads especially important on downhill roadsides, and along coastal and flatland roadsides). Approaches to integrate such solutions are further addressed in the *Ecotone* guidelines.

Box 4: Traffic volume considerations

The available scientific literature suggests that the magnitude of most road impacts increases according to the increasing of traffic volume. For this reason, the landscape guidelines include some caveats concerning low- and high-traffic scenarios. The threshold between low- and high-traffic scenarios is a species-specific value, often depending also by other local factors. In order to identify a general threshold between low- and high-traffic scenarios that could be easily implemented in these landscape guidelines, a literature review was performed regarding the above mentioned seven major impacts (i.e. road-kills, habitat loss and fragmentation, biological invasions, light pollution, noise pollution, chemical pollution and hydrogeological alterations) for our target species (plants, invertebrates and small vertebrates).

First, the literature review suggests that not all road impacts increase with traffic volume. Some remarkable exceptions are hydrogeological alterations (affected by traffic volume, but mainly depending on climatic and geomorphological factors) and road-kills. In fact, wildlife-vehicle collisions mainly depend on species presence/abundance in road proximities (often mediated by species traits), and they usually show a species-specific quadratic function in relation to traffic volume (i.e. low road-kill rates in correspondence of low traffic volume, high road-kill rates in correspondence of medium traffic volume, and again low road-kill rates in correspondence of high traffic volume, due to the increasing of barrier effect). For these reasons, the low- and high-traffic scenarios included in landscape guidelines do not concern hydrogeological alterations and road-kills.

Most studies determining low- and high-traffic scenarios (and concerning the impact of habitat fragmentation, biological invasions, light, noise and chemical pollution on plants, invertebrates and small vertebrates) usually establish a threshold around 1000 vehicles/day. Therefore, this value represents the threshold also for low- and high-traffic scenarios in these landscape guidelines. Hence, for most roads, planning roadside habitats is done under high-traffic scenarios, where the road may have a significantly negative impact on biodiversity and ecological processes.

An important final remark: the studies included in the above mentioned literature review describe the presence of road impacts on target species, but almost none of them consider the effect on population persistence, which is often unknown. As a consequence, the opportunity for promoting the presence of given species in high-traffic roadsides should be carefully considered by local managers, always evaluating the probability of population persistence in relation to the local context and the available scientific literature on the target species.

Measures to limit noise pollution
Traffic noise can dominate the soundscape near roads in the form of low-frequency background noise, which may interfere with vocal communication in birds, amphibians and insects and with echolocation in bats. Native shrubs and artificial barriers should be established on roadsides to reduce noise dispersion, especially in high-traffic scenarios (most important on downhill roadsides of mountain roads, and both roadsides in flatland and open-land roads). Local knowledge on vulnerable species

can be used to target measures, such as reduced traffic speed, during critical phases of vocalization in birds and amphibians, or barriers that are more efficient close to protected habitats.

Measures to limit chemical pollution
Road-derived contaminants have potential negative effects on the fitness of organisms through low-dose chronic exposure to a mixture of compounds. The impact on populations is however not well documented, so a precautionary approach is suggested.

Plants are hardly affected directly by contaminant levels in roadsides (except high accumulation of salts), but responses in animals are expected to be more severe. Hence, in landscapes with high chemical pollution (i.e., high-traffic scenarios), the presence of conservation-concern species (plants and especially animals) on roadsides should be carefully considered (and avoided if population persistence is not guaranteed). Especially relevant for cold landscapes, downhill roadsides in mountains, and coastal roadsides for coastal roads.

Shelterbelts of trees and especially hedges have a potential to lower the dispersion of contaminants from roads through sedimentation and accumulation on leaves, but may increase the accumulation of contaminants in the roadside soil.

Measures to limit hydrogeological alterations
Erosion and landslides can be limited by establishing deep-rooted native vegetation on roadsides (especially in both humid and arid landscapes, mountains, drylands and coastal landscapes). Surface runoff can also be reduced by maintaining the infiltration capacity of the soil with sufficient soil depth and a well-developed root system. Long-term impact of altered hydrology by road projects on biodiversity and ecological functions, especially for wetlands, requires in-depth investigations and is beyond the scope of these guidelines.

5.2.2 Guidelines for specific landscapes

5.2.2.1 Climatic landscape features

Warm vs. cold landscapes

Warm landscapes are those areas characterised at least by one warm season per year (e.g. temperate areas in central Europe), while some warm landscapes have high temperatures throughout the year, such as southern regions of the Iberian Peninsula, according to the Köppen-Geiger climate classification (at least one month with average temperature above 10 °C) (Figure 5.2; 1A). Cold landscapes have no warm season at all, e.g., the high elevation of mountain ranges, especially the Alps and the Scandinavian mountains, and some regions with arctic climate in Scandinavia (Figure 5.2; 1B). Note, that these patterns are expected to change with global warming.

Figure 5.2: Examples of dichotomies for climatic features: Categories 1A) warm vs. 1B) cold landscapes, 2A) snowy or frosty vs. 2B) snowless or frostless landscapes, and 3A) humid vs. 3B) arid landscapes. All pictures have been obtained from open repositories.

Key results of the review

- ✓ *Road-kills*: In warm landscapes, temperatures at roads can promote basking behaviour by insects and reptiles.
- ✓ *Biological invasions*: Cold temperatures are one of main barriers to the establishment of invasive species (especially plants), and for this reason biological invasions are more common in warm landscapes, especially under high-traffic scenarios.
- ✓ *Chemical pollution*: High solar radiation (and thus high temperature) reduces the persistence of contaminants (especially for volatile compounds), and for this reason the persistence of pollutants tends to be higher in cold landscapes. High-traffic scenarios mean higher emissions. The use of de-icing salts also causes a higher pollution load in cold regions.

Interpretation

- o High temperatures in warm landscapes promote physiological and behavioural processes in some species, potentially increasing certain road impacts such as road-kills and biological invasions (mainly plant invasions).
- o Low temperatures of cold landscapes promote persistence of volatile pollutants.

Guidelines

- ➢ In warm landscapes, rocky outcrops, sand and/or gravel patches should be provided along roadside habitats to attract basking activity that is otherwise performed on the road shoulder and thus reduce road-kill of insects and reptiles.

Snowy or frosty vs. snowless or frostless landscapes

Snowy or frosty landscapes (hereafter SF landscapes; Figure 5.2; 2A) are areas where snow and/or frost cover persist at least during winter months (e.g. Scandinavian countries), whereas snowless or frostless landscapes (Figure 5.2; 2B) are areas with very rare snow or frost accumulation (e.g. Mediterranean lowlands).

Key results of the review

- ✓ *Road-kills*: De-icing salt used in SF landscapes attracts ungulates and passerines, thus increasing road-kills. In snowy conditions, the road itself can represent an energy-saving pathway for many animal species.
- ✓ *Biological invasions:* The use of de-icing salt in SF landscapes can promote the spreading of exotic halophytes.
- ✓ *Chemical pollution*: De-icing salt used in SF landscapes affects soil chemistry and runoff water, having toxic effects on plants and animals (especially amphibians), including by interacting with heavy metals.
- ✓ *Hydrogeological alterations*: The use of de-icing salt in SF landscapes decreases soil permeability and aeration, while increasing surface runoff and erosion.

Interpretation

- o In SF landscapes, de-icing salt has important ecological consequences by increasing several road impacts on physical environment, plants and wildlife.

Guidelines

- ➢ In SF landscapes, chemical pollution and hydrogeological alterations should be mitigated by replacing de-icing salt with alternative inorganic and organic compounds.

Humid vs. arid landscapes

Humid landscapes (Figure 5.1; 3A) are characterised by temperate oceanic climate and abundant rainfall throughout the year (e.g. Ireland or north-western regions of the Iberian Peninsula and France, Köppen-Geiger Cfb and Cfc), whereas arid landscapes (Figure 5.1; 3B) are characterised by scarce rainfall, concentrated during short periods of the year (e.g. southern regions of the Iberian and Italian Peninsulas).

Key results of the review

- ✓ *Road-kills*: In humid landscapes, heavy rains reduce visibility of both drivers and wildlife, thus increasing road-kill probability. Similarly, high rainfall facilitates the growth of roadside vegetation, also decreasing visibility of drivers and wildlife.

- ✓ *Habitat fragmentation and connectivity*: In arid landscapes, roadsides are usually moister than the surroundings (due to run-off or microclimatic conditions), hosting higher diversity of both plants and animals.
- ✓ *Chemical pollution*: In humid landscapes, wash-off processes suspend contaminant particles and transport them to roadsides; high-traffic scenarios mean higher emissions.
- ✓ *Hydrogeological alterations*: In humid landscapes, high precipitation can increase runoff, water erosion and landslides, whereas the dry roadside soils of arid landscapes can be affected by wind erosion, but also by water erosion and landslides in the case of sudden rainstorms or flash flooding.

Interpretation

- In humid landscapes, heavy rains reinforce several road impacts (such as road-kills, spread of chemical pollution and hydrological alterations), with negative consequences on biodiversity, but also on human safety.
- In arid landscapes, roadsides can be moister than the surrounding landscape, thus hosting higher abundance of surrounding species (‘oasis effect’), or may be as dry as their surroundings (being potentially affected by hydrogeological alterations).

Guidelines

- ➢ In arid landscapes, microclimatic conditions that increase roadside moisture should be promoted, in order to constiture suitable habitats for surrounding species (especially in low-traffic scenarios, and always controlling for invasive species).

5.2.2.2 Geomorphological landscape features

Mountains vs. flatlands

Mountainous landscapes (Figure 5.3; 4A) are characterised by marked variation in elevation (e.g. high mountains such as the Alps, and ranges with lesser elevations such as the Vosges), whereas flatlands (Figure 5.3; 4B) are regions that lack significant variation in surface elevation (e.g. lowlands such as the Padan Plain in Italy or high plateaux such as the Spanish Meseta).

Figure 5.3: Examples of dichotomies for geomorphological features: Categories 4A) mountainous landscapes vs. 4B) flatlands, 5A) wetlands vs. 5B) drylands, and 6A) coastal vs. 6B) inland landscapes. All pictures have been obtained from open repositories.

Key results of the review

- ✓ *Road-kills*: For mountain roads, the typical steep slopes of uphill roadsides increase the barrier effect and promote wildlife movements along the road, leading to higher road-kill risk.
- ✓ *Habitat fragmentation and connectivity*: The distribution of mountain species (especially plants, but also animals) is naturally fragmented, and fragmentation increases under high-traffic scenarios.
- ✓ *Biological invasions*: The elevational gradients of climatic conditions are effective barriers to the establishment of invasive species (especially plants), and for this reason biological invasions are more common in lowlands, especially under high-traffic scenarios.
- ✓ *Light and noise pollution*: For mountain roads, the typical shape of downhill roadsides facilitates the asymmetrical spread of light and sound pollution, whereas flatlands are more evenly affected on both sides of the road; light and sound pollution increases in high-traffic scenarios.
- ✓ *Chemical pollution*: For mountain roads, the typical shape of downhill roadsides facilitates the asymmetrical spread of chemical pollution and high-traffic scenarios imply higher emissions.

- ✓ *Hydrogeological alterations*: Steep roadside slopes are exposed to surface erosion (by water and wind) and landslide risk.

Interpretation

- o Mountain roads typically have down- and uphill roadsides that determine asymmetrical spread of road impacts; roadside slope can further exacerbate this mechanism.
- o Flatland roads have symmetric roadsides, so negative road impacts penetrate with similar intensity in the surrounding landscape.

Guidelines

- ➢ For road-kills in mountain landscapes, see also 5.2.1. Downhill roadside vegetation should be managed to be unattractive for potentially road-killed wildlife. Escape ramps (artificial structures or made by plants or dead wood) should be installed on uphill roadsides with steep slopes, in order to provide an escape path for wildlife on the road.
- ➢ For light pollution along mountain and flatland roads, see 5.2.1. Mitigated street lamps should be installed only on the downhill roadside (light pollution directed towards uphill).
- ➢ For hydrogeological alterations along mountain roads, see 5.2.1, but also consided metal nets or geotextiles on roadsides with steep slopes, especially uphill.

Wetlands vs. drylands

Wetlands (Figure 5.3; 5A) are ecosystems permanently or seasonally flooded by water, such as marshes, swamps, fens, peatlands, bogs, lakes, lagoons, deltas and estuaries, or even artificial environments such as rice fields. Drylands (Figure 5.3; 5B) are environments in which precipitation (usually very low) is balanced by high evapotranspiration, so they are characterised by high humidity and sparse vegetation, such as steppes, scrublands, deserts and dunes, but also non-irrigated farmland such the Iberian Dehesa or Montado.

Key results of the review

- ✓ *Road-kills*: In wetlands, semi-aquatic species (e.g. toads) are more mobile than more aquatic species (e.g. frogs), and therefore they are more often road-killed, especially in transition areas between land and water.
- ✓ *Habitat fragmentation and connectivity*: The distribution of some wetland species (both plants and animals) is naturally fragmented, and this fragmentation increases under high-traffic scenarios. In drylands, roadsides are usually moister than the surroundings, allowing higher densities of local plants and animals.
- ✓ *Biological invasions*: Wetlands are prone to aquatic invasion (for both plants and animals), especially under high-traffic scenarios.
- ✓ *Light pollution*: Wetlands host high insect diversity, and several species are affected by artificial light, with negative consequences for their survival.

- ✓ *Hydrogeological alterations*: In drylands, roadside soils can be affected by wind, but also by water erosion and landslides in the case of sudden rainstorms with flash floods.

Interpretation

- o Wetlands are affected by road impacts on hydrological conditions and species movements.
- o Dryland roadsides can be moister than, or as dry as, the surrounding landscape, with different consequences on related road impacts.

Guidelines

- ➢ Along wetland roads, road-kill of small vertebrates (especially amphibians and reptiles) can be mitigated by establishing drift fences along roads (always combined with wildlife road-crossing structures). Drift fence effectiveness should be ensured by vegetation maintenance and by establishing native (short) grassland at roadsides.
- ➢ In drylands, microclimatic conditions that increase roadside moisture should be maintained aiming at allowing higher densities of local plants and animals (especially in low-traffic scenarios).

Coastal vs. inland landscapes

Coastal landscapes (Figure 5.3; 6A) are regions affected by proximity to the sea, while they can be flat coasts or rocky cliffs. Inland landscapes (Figure 5.3; 6B) are all the interior areas not affected by proximity to the sea.

Key results of the review

- ✓ *Road-kills*: Coastal species rarely move inland, whereas inland species move to coastal habitats rather frequently. For this reason, on coastal roads road-killed inland species are more common than coastal species.
- ✓ *Habitat fragmentation and connectivity*: The distribution of some coastal species (especially on rocky cliffs) is naturally fragmented (especially concerning plants, but also for animals), and this fragmentation increases under high-traffic scenarios.
- ✓ *Biological invasions*: Coastal landscapes are particularly prone to biological invasion (especially by plants); under high-traffic scenarios invasion risks increase.
- ✓ *Light pollution*: Nocturnal seabirds and newborn sea turtles are affected by artificial light on coastal roads, with negative consequences for their survival.
- ✓ *Hydrogeological alterations*: Sea cliffs are affected by surface erosion and rockslides.

Interpretation

- o Coastal roads typically have coastal and inland roadsides, resulting in asymmetrical spread of road impacts, most of them threatening the adjacent marine environment.

Guidelines

- For road-kills along coastal roads, see 5.2.1. The vegetation of inland roadsides can be also managed to be unattractive for potentially affected wildlife.
- For light pollution along coastal roads, see 5.2.1. Mitigated street lamps should be installed only on the coastal roadside (light pollution directed towards inland).
- For hydrogeological alterations along coastal roads, see 5.2.1, but also consider metal nets or geotextiles on coastal cliffs and dunes.

5.2.2.3 Land-use landscape features

Forests vs. open land

Forests (Figure 5.4; 7A) are areas spanning >0.5 ha dominated by trees >5 m with a cover of >10% of the total surface (FAO), and we include in our definition both natural forests and forestry. Open land (Figure 5.4; 7B) refers to environments dominated by herbaceous plants and shrubs, mainly without trees.

Figure 5.4: Examples of dichotomies for land-use features: Categories 7A) forest vs. 7B) open land, 8A) extensive vs. 8B) intensive landscapes, and 9A) homogeneous vs. 9B) heterogeneous landscapes**.** All pictures have been obtained from open repositories.

<u>Key results of the review</u>

- ✓ *Road-kills*: In forest landscapes, roadside vegetation reduces visibility of both drivers and wildlife, increasing road-kill probability.
- ✓ *Habitat fragmentation and connectivity*: Both forests and open land can be highly fragmented, naturally and artificially (i.e. in high-traffic scenarios), and this impact usually affect more species in natural ecosystems.
- ✓ *Biological invasions*: Open land is particularly prone to biological invasions (mainly by plants), especially under high-traffic scenarios.
- ✓ *Light and Noise pollution*: In open land, light and noise pollutions affect wide areas on both sides of the road, especially in high-traffic scenarios.

Interpretation

- o The steep ecotone between forest and road exacerbates some road impacts, such as road-kills and fragmentation.
- o The intrinsic habitat structure of open land promotes the spread of several road-related emissions to the matrix habitat.

Guidelines

- ➢ Follow the general guidelines in 5.2.1

Extensive vs. intensive landscapes

Extensive landscapes (Figure 5.4; 8A) are characterised by low and medium levels of anthropization and land-use intensity of low fragmentation, such as natural areas and extensive farmlands. Intensive landscapes (Figure 5.4; 8B) are areas characterised by the opposite, such as fragmented urban and peri-urban areas and rural areas with intensive agriculture or intensive forestry.

Key results of the review

- ✓ *Road-kills*: Natural wildlife corridors (such as streams and hedgerows perpendicular to the road) are road-kill hotspots in extensive landscapes, and even more in intensive landscapes.
- ✓ *Habitat fragmentation and connectivity*: Extensive farmlands are moderately affected by habitat fragmentation, whereas all intensive landscapes (both intensive farmland urban and peri-urban areas) are more often fragmented.
- ✓ *Biological invasions*: Landscapes with intensive land use are most prone to biological invasions (for both plants and animals), especially in high-traffic scenarios.
- ✓ *Light, Noise and Chemical pollution*: These impacts are more widespread in intensive landscapes, while extensive landscapes (and especially natural areas) host higher biodiversity, have lower background levels and can be more affected by change.

Interpretation

- o Extensive landscapes are characterised by low or medium levels of anthropization, so road-related emissions are low. Nevertheless, these landscapes host high biodiversity that can be heavily affected even by low levels of road-related emissions.
- o Intensive landscapes show the opposite patterns, but synanthropic and human-tolerant species (both plants and animals) can also be heavily affected.

Guidelines

- ➢ Follow the general guidelines in 5.2.1

Homogeneous vs. heterogeneous landscapes

Homogeneous landscapes (Figure 5.4; 9A) are relatively large areas (>50 ha) with similar characteristics in terms of land use, and they can be natural (forests) or artificial (intensive farmland) landscapes. Heterogeneous landscapes (Figure 5.4; 9B) are mosaic areas characterised by different land-cover types, and they can be natural (open forest) or artificial (extensive farmland) landscapes.

Key results of the review

- ✓ *Road-kills*: Natural wildlife corridors (such as streams and hedgerows perpendicular to the road) are road-kill hotspots in heterogeneous landscapes and even more so in homogeneous landscapes.
- ✓ *Habitat fragmentation and connectivity*: Heterogeneous landscapes can be fragmented naturally or artificially, and this fragmentation increases under high-traffic scenarios.
- ✓ *Biological invasions*: Homogeneous landscapes are particularly prone to biological invasions (especially by plants, but also by animals), especially in high-traffic scenarios.

Interpretation

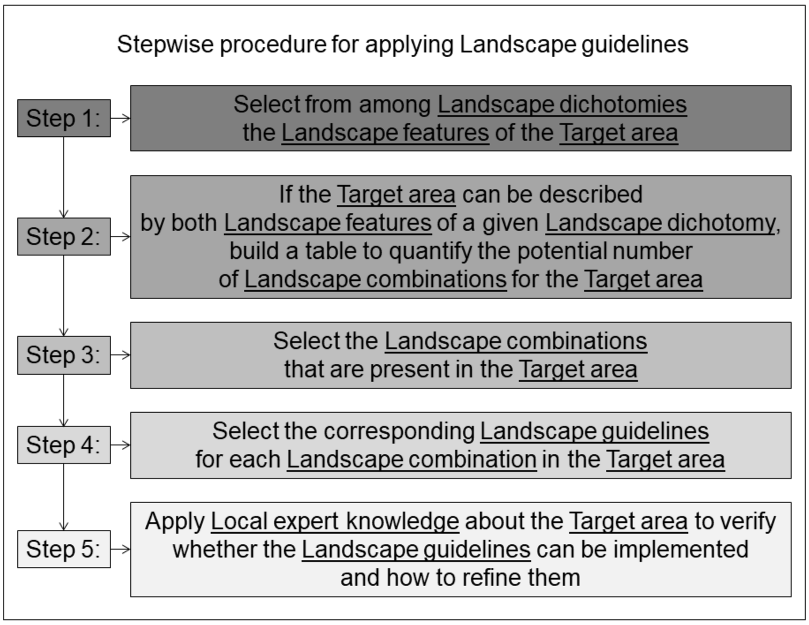
- The uniformity of homogeneous landscapes promotes the spread of some road-related impacts (e.g. biological invasions) and the aggregation of other impacts (e.g. road-kills).
- The complex structure of heterogeneous landscapes entails an intrinsic fragmentation that can be exacerbated by anthropization.

Guidelines

- ➢ Follow the general guidelines in 5.2.1 and box 5

5.3 Stepwise procedure for landscape guidelines

A single dichotomy is not enough to describe a given landscape. In fact, any given European landscape can be probably classified by choosing at least one landscape type for each dichotomy mentioned above. Thus, we propose a stepwise procedure for selecting the most suitable guidelines for designing and managing roadsides hosting high biodiversity in a given target area of Europe. The stepwise procedure comprises the following five steps (see Annex 2 for an example of stepwise procedure based on two target areas: Doñana National Park in south-western Spain and a small road in a Scandinavian forested landscape):



Some guidelines referring to different landscape dichotomies will converge, while others will diverge. In those latter cases, road planners should prioritise the most relevant guidelines based on local knowledge (such as species inventories, local information on threats, conservation priorities and targets, etc.).

Box 5: How to design and manage roadsides as corridors for dispersal

To contribute to EU biodiversity targets, road projects have to counteract negative impacts of landscape fragmentation caused by infrastructure networks. One of the most obvious measures could be to use roadsides to connect habitat patches along roads and within the wider landscape, and thus to increase its structural and functional connectivity. For many species, this would provide access to larger areas and more resources and allow dispersal and gene flow for isolated populations in the degraded landscapes of Europe. The associated risks and potential negative effects are however considerable.

The use of habitat corridors as conservation tools has been explored for decades (Gustafsson & Hansson 1997), but for roadside corridors the evidence is inconclusive. Although there are good examples that roadsides function as corridors and/or habitats, and in some cases as refugia, recent reviews stress the weak scientific basis for the corridor functions, due to rather few studies and their context dependence (Villemey et al. 2018, Ouédraogo et al. 2020, Lennartsson et al. 2021).

Key results

- ✓ While short-distance dispersal along roadsides is documented for a range of species, it is not well established how roadsides function as long-distance corridors.
- ✓ Roadsides that are high quality habitats may also function as corridors within and over generations, while low-quality habitats may still serve as corridors, especially for generalist species when the roadside does not lead to ecological trap effects. The spatial extent of the corridor functions is however not well documented.
- ✓ Invasive alien species and native weeds use roads as corridors for dispersal.
- ✓ The experimental evidence is weak, but our modelling work illustrate that the surrounding landscape matrix has a high impact on corridor functions, where high quality corridors are more important in low quality urban and agricultural landscapes. In these landscapes, the importance of roadsides is also higher both as potential habitats and as dispersal corridors,

Interpretation

- o Facilitation of connectivity from roads towards Natura 2000 sites and Annex 1 habitat types involves a considerable risk of introducing unwanted species.
- o Strategies for roadside habitats to contribute to biodiversity depend on the landscape context and the species-specific habitat specialisation, with different measures needed for high quality landscapes, those with high density of high-quality patches, and others with low density of high-quality patches.
- o The balance between risks of invasive species and the potential benefits of increased ecological connectivity needs to be addressed in roadside planning and operation.

Guidelines

- ➢ Evaluate risks of introducing unwanted species vs. the potential benefits based on the occurrence of critical elements of conservation concern, such as Annex 1 habitats or red-listed species within the wider landscape. If strategies for increased connectivity are potentially sensible, planning should follow the various recommendations from the *Ecotone* and *Habitats guidelines* to achieve high-quality connectivity.

    - o In high-quality landscapes with few barriers for dispersal, it is more important to prevent dispersal of invasive species along roads than to provide functional corridors.
    - o In fragmented landscapes with high-value habitats and barriers to dispersal across the landscape, high-quality roadsides should be developed to connect habitat patches and to provide structural connectivity. Here resources should be invested in suitable site conditions, vegetation development and suitable management and monitoring to provide continuity, and to prevent invasive species establishment.
    - o In low-quality landscapes, either fragmented by strong barriers to dispersal or with low density of high- to moderate-quality habitat patches, high-quality roadside should primarily be considered as refuge habitats.

In conclusion, the best approach for landscape connectivity would be to make continuous stretches of roadsides as good as possible for biodiversity and take measures to prevent dispersal of invasive species.

6 Ecotone guidelines

Summary

- The *Ecotone guidelines* support planning and management of roadsides with the ultimate goal of high biodiversity and ecosystem services. They supplement the *Landscape* and *Habitat guidelines*, with a focus on ecological gradients and habitat composition and configuration.
- The guidelines are based on a comprehensive literature review, including road impacts on plants, invertebrates, and small vertebrates in various regions. There was special attention on potential trap effects.
- Recommended are ecological gradients of intermediate length along and across roadsides. Midroad habitats should be avoided, and habitats should be different on adjacent roadsides to reduce traffic mortality. Roadside ecotones should allow connectivity with the surrounding landscape, with marked differences among target species. Evidence for ecological traps is limited, but red-listed species should not be encouraged at roadsides.

6.1 Introduction

A *roadside ecotone* is the transition zone between habitats within a road corridor. It is the joint expression of an environmental gradient (*ecocline*) and the associated community (*coenocline*). Most ecoclines are caused by variation in bedrock and soil, with marked effects on microclimate, soil moisture and nutrients. Within the guidelines, the term ‘ecotone’ is used for the entire sequence of habitats along an ecological gradient within the road corridor, i.e., for a series of transition zones from the road into the adjacent landscape (Figure 6.1).

Ecotones are rich in species and interactions, particularly when the transitions are spatially complex with contrasting ecological conditions and respective communities occurring at relatively short distances. The high biodiversity within ecotones is explained by three fundamental species–habitat interactions: (i) Some species are restricted to certain habitats, (ii) others depend on the specific conditions at habitat interfaces, while (iii) again others depend on a combination of several habitats, for example for larval and adult stages.

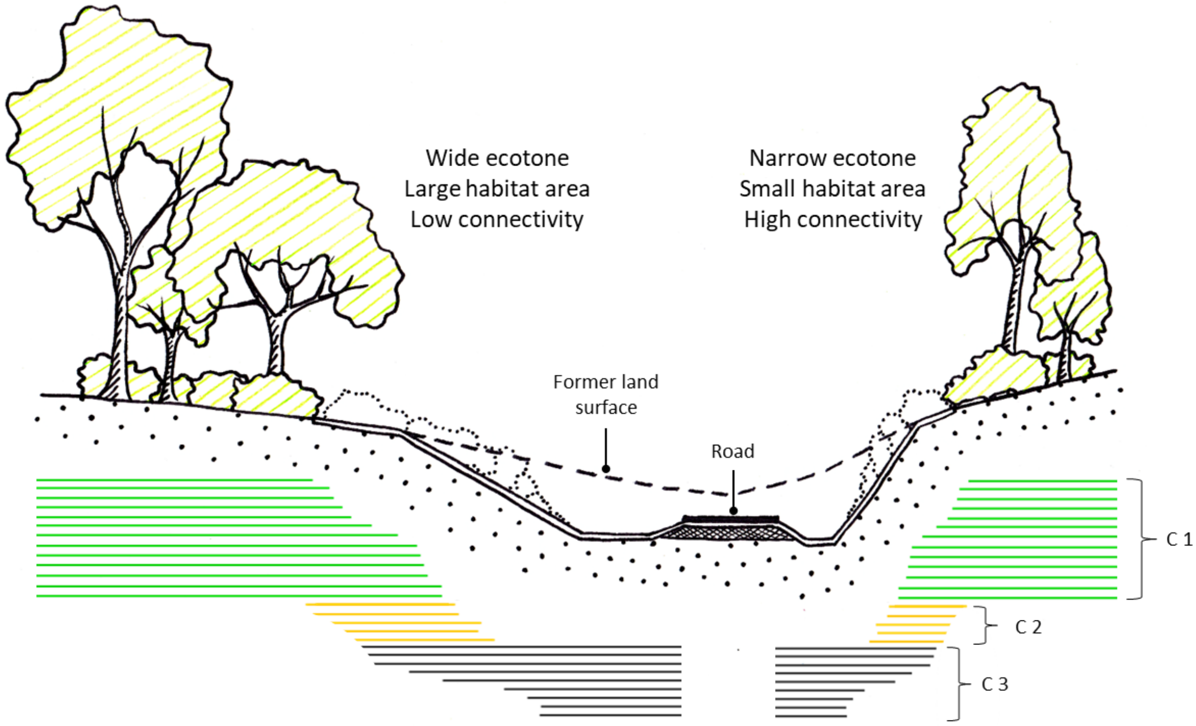


Figure 6.1: Roadside ecotone with a gradient of site conditions determined by a sequence of woodland, scrubland, and grassland vegetation. The ecotone results in staggered occurrences of plant, animal or microbial species that constitute distinct communities (C1–3). Road planning and maintenance can result in wide or narrow ecotones with marked effects on habitat area and connectivity, that control biodiversity and ecological functions (drawing by Sarah Kollmann).

Thus, the characteristics of roadside ecotones have significant effects on animal, plant and microbial communities and the resulting ecological functions and ecosystem services. However, roadsides are sub-optimal habitats for many species because these ecotones experience several stress and disturbance effects, while such habitats still can attract individuals constituting at least transient populations, as for example shown for Willow Warblers (*Phylloscopus trochilus*) studied along Dutch roads (Reijnen and Foppen, 1994). In this research, it has been shown that mostly young males of *P. trochilus* breed nearby roads, while more experienced males occupy the more valuable habitats. In the sub-optimal environment along roads, the breeding success is slightly lower, while territorial gaps in the population due to the death of one of the parents are quickly filled in by inflow of individuals from the surplus population.

When species are attracted to parts of the ecotone, but cannot survive or reproduce there, such ecotones may become populations sinks, i.e., *ecological traps*. Some species and guilds are more likely to experience such trap effects. This can be due to their specific behaviour, as observed for scavengers that feed on road-kill (Planello et al. 2015). However, at least some scavengers (crows and magpies) are opportunistic species that find many places to live, suffer from little competition or predation, and are favoured by man-made habitats. In these species, road mortality might be less significant, while the situation is different for reptiles basking on roads (Meek 2014), or species with a vulnerable life cycle, e.g., amphibians migrating to their traditional reproduction sites in spring (Deguise & Richardson 2009). Red-listed species are most seriously affected by any negative effects on their fitness and population dynamics, and therefore trap effects in roadsides have to be avoided if observed in these species, for example in orchids or other rare plants that colonise these refuge habitats, while the surrounding landscape has become inappropriate. In that case, reproduction can be reduced due to insufficient flowering, lack of pollination, inbreeding or poor seed set (Figure 6.2).

Roadside ecotones have different features than those at the habitat scale (see *Habitat guidelines*), and some target species of landscape planning and conservation depend on certain ecotones, as shown for many butterfly species. Ecotones link up to the surrounding landscape (see *Landscape guidelines*), and thus constitute an intermediate level of spatio-temporal complexity that must be considered during roadside planning, construction and management (Jakobsson et al. 2018).

6.2 Longitudinal and lateral gradients of roadside ecotones

<u>Key results of the review</u>

- ✓ Variation of ecotones <u>along</u> roads controls significant elements of biodiversity:
  - o Ecotone continuity along roads increases population size of target species and facilitates their dispersal (Le Viol et al. 2015).
  - o The resulting larger ecotone area supports higher species numbers (following the classical area–biodiversity relationship).

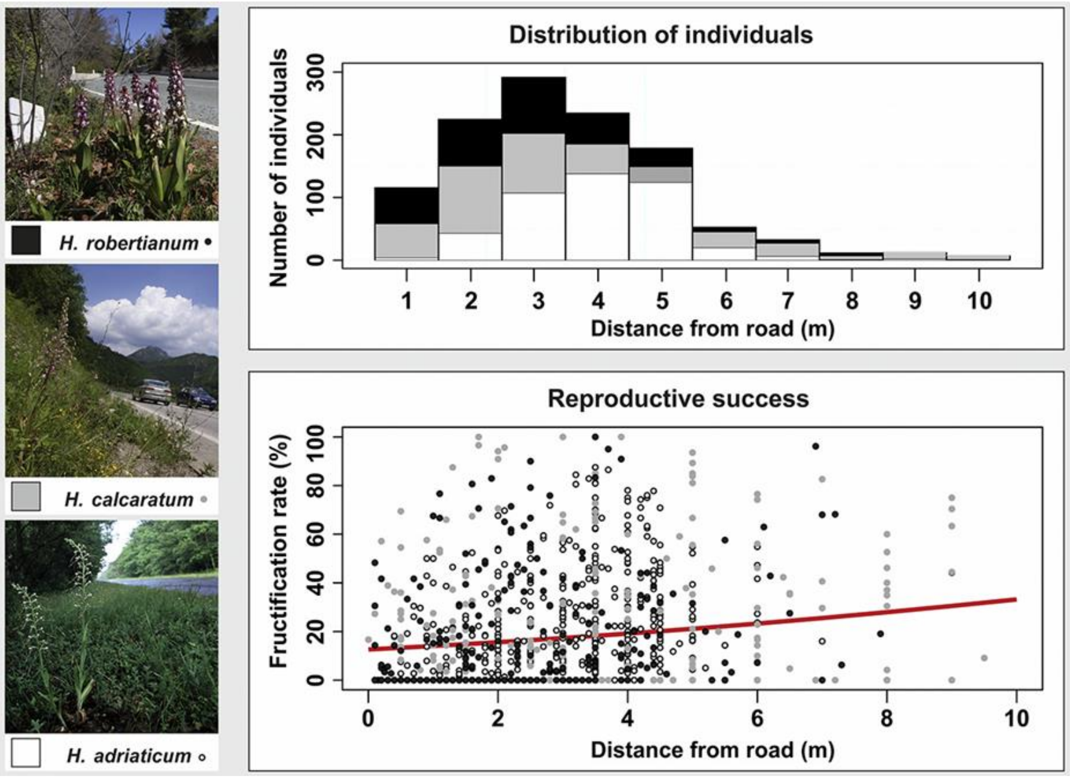


Figure 6.2: Relative distance from road and reproduction rates of individuals of three lizard orchids in southern and eastern Europe (Fekete et al. 2017). The combination of high plant densities at roadsides and reduced reproduction indicates an ecological trap effect. Reprinted with permission from <u>Elsevier</u>, Copyright (2017)

- ✓ Width of roadside ecotone controls other aspects of biodiversity (Figure 6.1).
  - o Wide[1] roadside ecotones are correlated with larger areas of the respective habitats and their contact zones; such ecotones support larger populations of more species.
  - o Narrow roadside ecotones enhance habitat connectivity, but also increase the risk of traffic mortality.
- ✓ Intermediate-width roadside ecotones support most biodiversity, because
  - o Narrow ecotones with very short ecological gradients provide many habitats, but with little area per habitat.
  - o Very wide (i.e., smooth) ecological gradients will not develop the distinct features of ecotones.
  - o Interactions among habitat specialists and establishment of multi-habitat species are encouraged by intermediate ecotone width.
- ✓ Habitat quality within roadside ecotones is of high importance for biodiversity (see *Habitat guidelines*):
  - o There are some ‘universally good’ roadside habitat qualities, i.e. nutrient-poor, dry and sun-exposed sites, or sites with no use of pesticides. Such habitats potentially support a rich biodiversity, but also suffer from stress and disturbance effects due to traffic.
  - o There are specific roadside habitats and ecological factors that attract certain target species, e.g., rocky outcrops or ditches (Homyak et al. 2014).
  - o This increases biodiversity within the respective habitats and for the entire series of ecotones.
- ✓ There is considerable variation among species groups in response to roadside ecotones:
  - o Bigger species use larger habitat patches and wider ecotones.
  - o Mobile and opportunistic species are better able to also utilise small habitat patches, since patch extinctions can be balanced by (re)colonisation; this applies, for example, for invasive alien species (McDougall et al. 2018).
  - o There are no systematic differences in ecotone usage and the resulting fitness between species with slow or fast life cycles.
- ✓ Spatio-temporal dynamics of roadside ecotones depends on the constituting habitat types (see *Habitat guidelines*) (Milton et al. 2015):

[1] Within the EPICroads Guidelines, *narrow* roadsides are defined when extending over less than half of the road size; *intermediate* roadsides correspond to about road width, while *wide* roadsides exceed the width of the respective road.

  - Taller vegetation requires more ecotone area, because the constituent plants (tall herbs, shrubs, trees) need more space both along and across the roadside.
  - Vegetation at nutrient-rich sites develops faster, grows taller and requires larger areas within roadside ecotones.
  - The opposite is seen in plant communities of ecotones with limiting resources, i.e., dry, nutrient-poor soil with extreme pH, or frequent disturbance by mowing, fire or erosion.
- ✓ Longitudinal and lateral effects of roadside ecotones vary among regions (*Landscape guidelines*):
  - In intensively used landscapes, roadside ecotones are more nutrient-rich and well supplied with soil moisture, and thus require wider ecotones.
  - Southern European roadside ecotones (and those in lowlands) are more species-rich, and thus require more targeted management (Jakobsson et al. 2018).
  - Ecotones in historical and/or montane landscapes support the highest levels of biodiversity.

<u>Interpretation</u>

- Well-connected and wide roadside ecotones allow species-rich animal, plant and microbial communities with high numbers of functional interactions.
- A network of ecotones leads to habitat continuity across and along roads, with higher benefits for mobile compared to sedentary species.
- Both habitat generalists and specialists can maintain persistent populations within roadside ecotones, independent of their (regional) rarity.
- Species that have low mobility and do not require large habitat areas can persist within relatively small roadside ecotones.
- High biodiversity in roadside ecotones will result in multiple ecosystem services, i.e., erosion control, stormwater infiltration, pollination, landscape aesthetics etc. (O'Sullivan et al. 2017).

<u>Guidelines</u>

Step 1. Roadside planning

- ➢ Early in the planning process, a decision tree should be worked through based on the *Habitat* and *Landscape guidelines*: In which region will the ecotone be placed? At which altitude and relief? On which bedrock and soil? Within which historical landscape? Along which road category? Which habitats could constitute the ecotone(s)? Which (natural) temporal dynamics are to be expected? Which management is feasible? Which target species (groups) should benefit from the ecotone? To what degree are these species affected by dispersal limitations and by site limitations? And finally: Are species of conservation concern or invasive alien species included?

- Answering these questions will moderate the significance of the key results mentioned above, and lead to site-specific decisions during the planning process.
- A lateral and longitudinal network of roadside ecotones should be planned, with complex and wide transition zones between habitats, depending on land availability, plant size and growth form, and the risk of ecological traps or biological invasions (Figure 6.3).
- Ecosystem (dis)services, e.g., increased erosion or attraction of invasive alien species, of certain ecotones need to be considered during the planning process.

Step 2. Roadside construction

- Roadside habitats and the resulting ecotones should be made as wide as possible within the constraints of landowners and construction regulations. Wide roadsides would also allow for marked ecological gradients. However, given the limited space within the road corridor, it is unlikely that the ecotones can become too wide.
- Narrow and steep roadsides lead to close contact between different habitats, thus producing pronounced ecotones that can be beneficial for biodiversity (cf. Figure 6.1). However, they are discouraged because they result in small habitats that need more frequent management, and result in higher risk of road-kill (because animals live more closely to the road) and increased erosion of steep slopes. Here, prevention of erosion and mass movements would require slope stabilisation by concrete structures, wire nets, geotextiles or dense (grass) vegetation, often resulting in reduced biodiversity.
- Non-endangered habitat generalists and specialists (both of plants and animals) should be introduced or encouraged. So far, there is little experience in promoting specific microbial communities, for example by using certain soils or by soil inocculation, although microbes at least partly control vegetation development (e.g., Wubs et al. 2016).
- The focus should be on species with small habitat requirements and low mobility, depending on width of the ecotone.

Figure 6.3: Roadside of a motorway near the city of Hof in northern Bavaria. The immediate road verge is relatively rich in soil resources and supports a frequently mown species-poor grassland, whereas the steep sloping roadside on diabase bedrock is only sparsely covered by plants. To foster re-vegetation, the invasive alien *Lupinus polyphyllus* was planted, while the site would be ideal for rare annual plant communities that could be actively introduced from near-by natural rocky outcrops.

- Rare (red-listed) species should be discouraged when and where trap effects can be expected, e.g., for narrow roadside habitats in combination with heavy traffic.
- Seeds or plants should be of regional origin (including no cultivars) to achieve viable populations and functional interactions (Bucharova et al. 2019). This has become mandatory in EU countries since 2020 but is still not implemented in most regions due to lack of practical experience and low seed availability.
- Establishment of invasive alien plant and animal species (*neobiota*) should be avoided by increasing the biotic resistance of roadside ecotones, and by reducing connectivity in areas prone to invasions (Figure 6.3).

Step 3. Roadside management

- There should be some lateral and longitudinal variation in ecotone management (mowing, pruning, cutting, burning), and the management should be adapted to the type of roadside habitat (soil type, vegetation type etc., see *Habitat guidelines*). However, management must respect the requirements of the target species (to be defined in each road project) and should not change too often, because this would favour generalists. Management would be unsuitable if it facilitates colonisation and local expansion of invasive neobiota.

- Management should maintain or increase the area of roadside ecotones, i.e., encroachment of dominant species from the adjacent habitats should be prevented, as this would spatially shift or destroy the ecotone.
- Changes in habitat area, vegetation structure, species composition and population trends should be monitored (Steinfeld et al. 2011), in order to maintain target species or specific ecological processes, and to exclude unwanted species. The monitoring interval should increase with time (e.g., 1, 2, 4, 8, 16 yrs), albeit depending on the life cycle of target species and resource availability of the road sites.
- Costs for ecotone design, planting, monitoring, and management should be considered already during the planning phase of roads.

6.3 Avoiding ecological trap effects of roadsides

Key results of the review

The likelihood of trap effects occurring is determined by a combination of factors that are also addressed in the *Landscape* and *Habitat guidelines*:

- ✓ Most important: The proportion of the (meta)population that occurs at the roadside determines the risk of roadsides functioning as ecological traps.
- ✓ Attractiveness of the roadside habitat (in broad terms, including resource habitats) in relation to the surrounding habitats; this controls whether individuals are more likely to choose the roadside than similar habitats elsewhere.
- ✓ Availability of suitable habitats at the roadside in relation to availability in the surrounding landscape.
- ✓ Suitability of the roadside as a habitat for reproduction, which drives the population growth rate; this in turn is the result of several factors, ultimately determining the balance between recruitment and mortality.
- ✓ Direct mortality in the roadside environment, i.e., the actual roadside habitat and the road, if species are crossing it (Meek 2014, Deguise & Richardson 2009). This is the result of other factors in combination, such as roadside width (see above), distance from traffic to the spot in the roadside where the species are spending their time, traffic volume, mobility and behaviour of the species, and the use and presence of fauna crossing measures.
- ✓ Thus, a combination of contrasting habitats or factors constitute ecological traps (Figure 4):
    - Certain ecological factors are attractive for a species.
    - Fitness and population growth are low in that area, while mortality may be high.
- ✓ The trap effect depends on the type of roadside ecotone:
    - Narrow ecotones with steep gradients are more likely to create ecological traps.
    - Unsuitable habitats that lack essential resources constitute traps.

- Similar habitats on both sides of a road enhance trap effects due to increased road crossings, resulting in more frequent road-kills.
- Lack of connectivity contributes to trap effects because isolated populations cannot benefit from immigration or emigration of individuals.

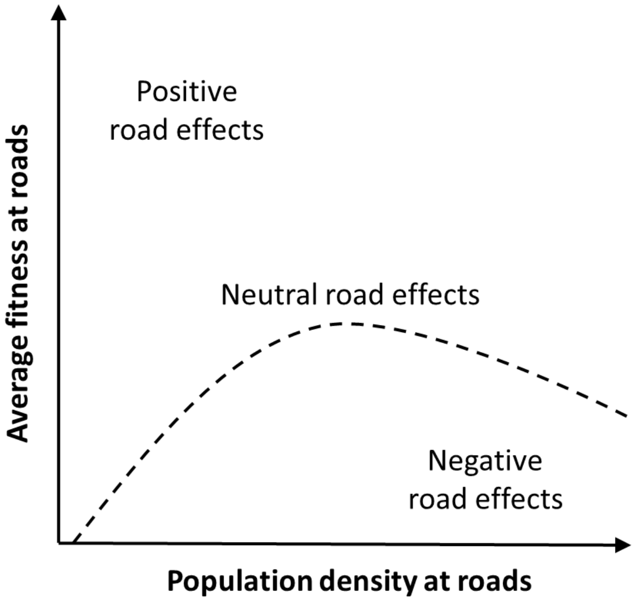


Figure 6.4: Populations of plant and animals occur at species-specific densities along roadsides. Average fitness of these populations, measured as the number of offspring per individual, increases at moderate densities, while it shows a negative relationship at high densities. Deviating from this fundamental relationship, roadsides can have positive effects on fitness due to particularly suitable habitats, e.g., for salt-tolerant plants or effective dispersal of invasive alien plants (upper left). However, they often have negative effects (lower right), that are called *ecological traps*, when local populations are high, but have high mortality and low reproduction, e.g., lizards and snakes basking on hot road surfaces, or passerines feeding and breeding in shrubland along roads. Neutral effects correspond to those observed in non-road habitats, as indicated by the broken line.

Interpretation

- Species-specific (potential) trap effects have to be considered during roadside planning.
- Well-connected and wide roadsides are less likely to constitute ecological traps.
- Species that need relatively large habitat areas and have high mobility are more likely to experience roadsides as traps.
- Depending on their life cycle, habitat requirements and mobility, species suffer to different degrees from ecological trap effects, and rare (red-listed) species are most heavily affected.

Guidelines

Step 1. Roadside planning

- Identify endangered and protected species that actually or potentially make use of the habitat(s) nearby the planned roadside, that later on are suspected to experience trap effects along the road.
- Plan roadsides with different habitat types on both sides of the road, e.g., shrubland vs. grassland, that do not encourage road crossings, e.g., by butterflies or passerine birds (Keilsohn et al. 2018).
- Review potential landscape factors that increase trap effects according to the list of landscape dichotomies described within the *Landscape guidelines*.

Step 2. Roadside construction

- Roadside ecotones should be designed to be at least as wide as the road is broad, while taking the specific needs of the target species into account. If the road corridor is wide enough to accommodate a series of (successional) habitats transversal to the road, the resulting ecotones would have reduced trap effects.
- The most valuable habitats should be established at some distance to the road.
- A network of roadside ecotones should be planned to connect fragmented populations, depending on landscape composition and configuration, and the specific needs of the target species.
- Attractive but fatal habitats should not be constructed, particularly in narrow road corridors.
- Non-endangered habitat generalists and specialists should be introduced or encouraged by sowing native-local seeds or green hay.
- Species with small habitat area requirements and low mobility should be promoted. This implies that there is usually no risk in introducing plant species, unless they are host plants for invertebrates that may experience lateral or longitudinal trap effects.
- Discourage rare (red-listed) species where and when affected by ecological trap effects.

Step 3. Roadside management

- Lateral and longitudinal variation in ecotone management, e.g., in frequency and intensity of mowing or pruning, would help with (meta)population dynamics. The resulting mosaic of different management would generate additional ecotones, and unmown sections could become refuges for sensitive animal species or stages.
- Management should maintain or increase the size and quality of roadside ecotones by regular mowing, pruning, or cutting, while changes in the adjacent landscape have to be considered as well.
- Management should not create favourable habitats that are population sinks.
- When a trap effect on target species is suspected, monitoring of the respective populations (numbers, fitness, mortality etc.) is necessary to understand the need for mitigation measures and for communication with roadside management authorities.

- Consider the costs of avoiding trap effects along roadside ecotones (e.g., due to extra construction efforts).

6.4 Conclusions

The *Ecotone guidelines* indicate that the quality of road ecotones can be improved as part of European green infrastructure (Garmendia et al. 2016), and that the likelihood of trap effects can be reduced through clever design of the roadside habitat (Kallioniemi et al. 2017). This means that (i) roadsides should be as wide and as elevated as possible given landscape constraints, (ii) essential resources for plants and animals should be located away from the traffic, (iii) at dangerous roads (e.g. with narrow roadsides and heavy traffic), attractive ecotones, roadside habitats or resources should not be offered, or offered mainly for non-mobile species, (iv) similar habitats on both roadsides should be discouraged, and (v) favourable ecotones should not be placed in landscapes where they create trap effects.

7 Habitat guidelines

Summary

- In a review of biodiversity in roadside habitats (with focus on plants and insects) we have identified a number of fairly general patterns of biodiversity response to different measures for roadside construction.
- The guidelines provide solutions on how to overcome constraints and to realise the potentials in the landscape by creating and maintaining roadsides that function as high-quality habitats and as corridors for dispersal.
- The respective guidelines highlight soil characteristics, exposure, local species pools and dispersal limitations as critical for roadside construction, but also measures to maintain heterogeneity and sufficient length of roadside stretches targeted for biodiversity.
- Management regimes to prevent competitive exclusion of species and maintain ecological functions over time are critical and have to be adjusted to bedrock, soil, climate, and vegetation. Guidelines also help in identifying sections of road with higher potential for biodiversity and in providing prioritisation based on both site and landscape context. This includes the importance of historic legacy and conservation concerns.

7.1 Introduction

When constructing a new road, and rebuilding or when managing an existing road, there is often great potential to promote biodiversity, e.g., species of conservation concern, by creating and maintaining suitable roadside habitats. However, the ecological potential varies along the stretch of the road depending on e.g., type of soil in the road corridor, topography, vegetation, and the ecosystems surrounding the road (Villemey et al. 2018). It is further influenced by constraints and possibilities related to practical, economic, aesthetic, safety issues etc., which will influence the final decision of what to do where. These habitat guidelines do not discuss relationships between biodiversity and other values and needs related to roads but can help in identifying road and landscape conditions and suitable methods for construction and management, which offer the best ecological potential to promote biodiversity of conservation concern (O'Sullivan et al. 2017).

Roadside habitats for biodiversity are formed mainly through suitable use of local soil and other material, constructing of structures that serve as habitats for species (slopes, surfaces etc.; Müllerová et al. 2011), and through proper use of methods for vegetation establishment. Guideline 7.2 recommends a number of measures for creating habitats for biodiversity when building a new road or rebuilding an existing road and helps identify stretches of the road where such measures are most effective.

The vegetation along roads is regularly cut for safety reasons and to secure technical functions necessary to maintain road infrastructure. Cutting also can favour species richness of the vegetation and invertebrate fauna, and various measures for 'ecological cutting' have been proposed in many countries. Although cut roadsides are often likened to hay meadows, there are large differences between the two groups of habitats. One major difference is that most roadsides are also subject to regular disturbances to the ground, for example through ditching and grading. Such disturbances mean that roadsides often have successional, sometimes ruderal, vegetation, rather than meadow vegetation. Another difference is that meadows are mown for hay whether most roadsides are cut without removing the cut material – frequently using mulching equipment. In notable exceptions, the cuttings are removed and composted or digested for biogas. To favour biodiversity in roadsides, practices for both vegetation and ground management need to be adapted. The efficiency of ecologically adapted management of vegetation and ground varies between different types of roadsides, mainly depending on successional stage, soil type, productivity of the vegetation and occurrence of competitive plants. Therefore, it is important to identify not only proper methods for cutting, ditching and so on, but also identify where to apply such measures. Guideline 7.3 helps identify sections of road where adapted management of ground and vegetation is most likely to favour biodiversity of conservation concern. It also helps select the best management for different types of roadside habitats.

The possibilities for species of conservation concern to utilise roadside habitats are ultimately limited by the properties of the roadside (see White 1979). The habitat conditions necessary for species need to be present in the roadside, and such conditions can be created by suitable roadside construction (7.2) and management (7.3). However, the efficiency of such measures strongly depends on how the roadside habitat interplays with the surrounding landscape. To optimise the potential of a road to promote biodiversity, it is necessary to consider the surrounding landscape in both construction and management (Noordijk et al. 2009, 2010). In most cases, roadside habitats should be constructed to resemble closely habitats of conservation concern in the landscape (Villemey et al. 2018). Resemblance here refers to ecological conditions and processes, i.e., factors that enable demanding species from a habitat in the landscape to colonise or use resources in a similar habitat in the roadside. Guideline 7.4 proposes a stepwise approach to linking road construction and management to the surrounding landscape to promote biodiversity of conservation concern.

The guidelines are based on a literature review (Lennartsson et al. 2021), to which we refer for further reading, and each guideline is introduced by showing the main results of the review. However, we have not included literature on the technical aspects of road construction and function. We consider, however, the recommendations in these guidelines to be in general realistic and not compromising road function. This assumption is supported by the fact that most of the recommendations also occur in various constellations in many national practical guidelines. In case a suggested measure for biodiversity critically compromises road function in a certain road or project, we assume that biodiversity is subordinate road functionality aspects, such as traffic safety and durability of the road construction.

We have not estimated costs for the suggested biodiversity measures. Some may carry increased costs compared to not implementing the measures, whereas other measures are cost-neutral or may reduce the costs compared to 'normal' road building and management. Exemples of reduced costs are to avoid topsoiling, to choose natural vegetation establishment instead of seeding, and to reduce the number of cuttings. Cost-efficiency may vary due to local societal and natural conditions. For example, cost-efficieny and general possibilities of constructing and maintaining biodiversity-rich road verges may be influenced by national policy and legislation, administrative routines etc. Such factors are country-specific and have not been considered in the guidelines. Finally, all actions for favouring biodiversity in road verges require that invasive plant species be suppressed. Measures for mitigating invasive species are not treated in the guidelines.

7.2 Construction of roadside habitats for biodiversity of conservation concern

Key results of the literature review

- ✓ Roadside habitats can be rich in vascular plants and invertebrates, also regarding specialists and threatened species.
- ✓ As in most other habitats, plant species richness in roadside habitats is higher on calcareous soils than on acidic soils. Greater plant species richness, in turn, supports a more species-rich fauna of invertebrates (Wrzesień & Denisow 2016).
- ✓ Roadside habitats can be colonised by plants from surrounding habitats. There are, however, considerable knowledge gaps regarding the efficiency of spontaneous colonisation, for example, which species groups colonise and, in particular, from what distances colonisation normally occur.
- ✓ Many roadside habitats are characterized by frequent disturbance to the ground. Disturbances creates bare soil and initiates vegetation succession and the establishment of pioneer species, many of which are of conservation concern, but also including invasive species.
- ✓ Low productivity is beneficial for plant species richness and for species of conservation concern, for two reasons:
  - o Low productivity slows down vegetation succession after soil disturbance, leading to longer periods of early and intermediate succession phases. Those phases are often more species-rich compared to later phases, in which the vegetation is dominated by fewer, competitive species. Early phases have more bare soil, which is beneficial for many ground-dwelling and digging insects, and for the establishment of plant species from adjacent habitats. Longer periods with sparse vegetation thus increase the chances of spontaneous colonization.
  - o Low productivity is essential for high species richness in mowing-generated grass swards because it prevents the domination of tall competitive species (Clark & Tilman 2008). The relationships between productivity and vegetation management are further addressed in the guideline for ground and vegetatiom management (**Feil! Fant ikke referansekilden.**).

- ✓ Low productivity is often associated with well drained, for example sandy, soils, and the choice of material for building the road is therefore crucial. Low-productive and dry conditions may be created also by high evapotranspiration in sun-exposed slopes.
- ✓ In some landscapes, nutrient-rich habitats may be hotspots for biodiversity. However, such habitats are usually difficult to construct and maintain in roadside environments, because the vegetation on nutrient-rich soils needs certain regular management not to become dominated by a few competitive species.
- ✓ Roadside ditches and other drainage constructions may provide wet or moist habitats and vegetation types, of great value for biodiversity (Zielinska et al. 2013).
- ✓ Measures for vegetation establishment, e.g., reuse of topsoiling and seeding, are rarely performed for biodiversity conservation reasons, but practices are usually applied in order to establish a vegetation cover rapidly. In some practical guidelines reuse of topsoil from the road corridor is suggested as a measure for establishing the local flora, but there are hardly any studies of the outcomes of topsoil reuse. and to be sure to (re)utilize the seed supply of locally established plant species.
- ✓ Newly constructed roadside habitats are extremely vulnerable to the establishment of invasive plant species that largely transform the habitats.

<u>Interpretation of the results</u>

- o Roadside habitats can make a considerable contribution to biodiversity conservation, through being suitable for many specialist species, being large in cumulative area (and often also in area of local habitat), and offering cost-efficient conservation options, not least in centres of urbanisation.
- o Road construction and management include considerable manipulation of the soil and ground. Since soil type and ground conditions are crucial for roadside habitats, road administration thus offers great potential for creating biodiversity-rich habitats that contribute to biodiversity conservation.
- o There are many knowledge gaps regarding relationships between soil type and roadside biodiversity. Knowledge gaps also include common practices such as the reuse of stripped topsoil to establish new vegetation.
- o The conservation benefits of roadsides differ among countries depending on which groups of species are nationally protected, threatened, and red-listed. Roadsides can provide a certain group, or range, of habitats, and the number of species of conservation concern that belongs to that group is larger in some countries than others. Through the design of roadsides, it is possible to influence, within certain limits, which habitats are created, and the design therefore should be adapted to conservation policies.
- o In contrast to most other types of nature, roadsides have rarely been subject to systematic classification based on structure, organism, communities, ecological conditions, processes etc. In order to create a foundation for assessment of biodiversity potentials and management needs, roadside habitats should be described using policy-relevant ecological frameworks, e.g., similar to the European Nature 2000 framework.
- o In spite of several important knowledge gaps, interpretation of research, biodiversity inventories and practical experience suggests a number of key

factors for biodiversity, related to soil and substrate, which can be used as a base for practical recommendations.

- In general, low-productivity soils have the best potential for forming biodiversity-rich habitats. Knowledge is lacking on whether there are also landscapes in which biodiversity is favoured by the creation of nutrient-rich roadsides. The importance and properties of wet ditch habitats have also been poorly investigated, although some examples indicate potential for creating moist habitats when building infrastructure.
- Successional, sparse, and initially ruderal vegetation on mineral-rich topsoil is easier to create in roadside habitats than grass sward vegetation, which takes a long time to develop.
- For the establishment of plant species of conservation concern in roadsides, it is not possible to rely entirely on spontaneous colonisation from surrounding habitats. Dispersal of some species or from some sites may need to be facilitated by active transfer of seeds or plants.
- Biodiversity connected to trees and forests is not addressed in these guielines, study, but roads probably have the potential to favour biodiversity of light-demanding shrubs and old trees, especially in the edge between an open road corridor and an adjacent forest, and in hedgerows (Forman & Baudry 1984) and tree avenues (Oleksa et al. 2009, 2013).

Guideline

Step 1. Mapping of roadside potential

Habitats for biodiversity of conservation concern can be formed by combining the topographic potential of a road with its soil potential. Through such combinations, it is possible to create suitable road structures (roadside inner and outer slopes, open surfaces, ditches etc.) on suitable soils. Therefore, the first step should be to map the soil types, topography, and planned road structures in the road corridor, in order to identify sections with the potential to create habitats for species of conservation concern.

In many parts of Europe, the highest potential is found where the road project will create slopes, cuts and surfaces on local soil of nutrient-poor and well-drained types, or where road sections are on calcareous soil. If non-local soil and road material is used to create habitats, such material also needs to be nutrient-poor, well drained and without a layer of nutrient-rich topsoil. The potential habitats should be treated in order to create low-productive vegetation with slow natural succession, see step 2.

Figure 7.1: Well-drained, sun-exposed high slope with high potential for slow succession and biodiversity of conservation concern. Överfors, Province of Södermanland, Sweden 2010.

Specific national targets for biodiversity conservation may indicate that other soil types and road structures, for example moist or more nutrient-rich soils, may provide potential in specific cases.

Light-demanding shrubs and trees of conservation concern may be favoured in the road corridor.

Criteria for prioritisation of sites for biodiversity measures along the road are:

- Potential height of slopes and width of flatter surfaces. Higher and wider roadsides are more valuable because they increase habitat area and can reduce the risk of traffic mortality for flying insects, since habitats are formed away from the traffic. Wider open roadsides also provide wider clear zones, thereby reducing risk of collision with larger animals.
- Potential length of habitat. Longer stretches of habitat are more valuable because of larger habitat area and increased potential for dispersal along the road. However, smaller pockets of e.g., sandy or calcareous soil are still a possible measure to favour biodiversity (next point).
- Soils suitable for digging insects, such as wild bees Sydenham et al. 2014), should be prioritised, also including where they occur in small deposits. For species groups like digging solitary bees and wasps, a few square metres of suitable open slope may be enough to establish a colony. There is a rather wide range of such soils, and occurrence of digging insects is an important indication of soil suitability.
- Structure variation by creating a patchwork of several smaller habitat patches situated a maximum of a few hundred metres apart may be as beneficial as one larger habitat area.

- South- and west-facing surfaces are more valuable for thermophilic insects (Sydenham et al. 2014). Such slopes also show a slower succession, at least in northern, mountainous, and Atlantic regions of Europe, where north-facing surfaces tend to become rapidly dominated by mosses or tall vegetation.
- Potential to create low-productive moist or wet habitats, for example in catchment areas for runoff water and attenuation ponds (for mosses, see Richter & McKnight 2014). Measures for creating wetland and shore habitats are particularly effective on calcareous soils and where moist and wet habitats are in ecological deficit.
- Potential to create low-growing shrub-rich habitats, either semi-natural shrub-grassland habitats or planted shrubs, such as hedgerows or ornamental plants.
- Potential to favour light-demanding old trees of conservation concern, either in the road corridor or at the edge between the open road corridor and adjacent wooded land.
- Nearby occurrence of species of conservation concern (according to regional conservation authorities or other sources) that can be favoured by roadside habitats. See 7.4 for further information about how to connect a road to the surrounding landscape.
- Stretches of a road where there is an obvious risk of creating an ecological trap should not be prioritised for creating habitats for species of conservation concern; see *Ecotone guidelines*. A trap is caused when individuals of a species are attracted to the roadside habitat but face a high risk of mortality or other reduced viability there.

Step 2. <u>Creating habitats</u>

The next step is to treat the prioritised sites in order to create roadside habitats with the best possible potential for biodiversity. The measures suggested below will create roadsides with high potential to develop persistent species-rich vegetation with species from the local flora. These types of habitats will thus be generally important for biodiversity in most landscapes. However, specific roadside habitats may be created in order to favour certain species in the landscape, or to address certain local conservation goals, see 7.4.

The construction of habitats for biodiversity should be communicated with roadside managers throughout the process, in order to make sure that the habitats are possible to manage in the future, and to explain the conservation targets for the new habitats (see Rosell et al. 2020).

When creating roadside habitats, there is room for innovative and local solutions, but the following measures are generally beneficial at sites where biodiversity is prioritised:

- In most cases, a general aim is to create surfaces that are as large as possible and have nutrient-poor and well-drained conditions that favour ruderal flowering plants, small species with poor competition capacity, slow succession, and sparse vegetation cover on soils suitable for digging bees and thermophilic invertebrates.

- Do not plant trees and shrubs on potential open spaces of the type described above; trees and shrubs will shade the habitat and increase the succession by elevating nutrient cycling through leaf litter.
- At least in northern, mountainous, and Atlantic climates, sun-exposed sites are preferable, whereas north-facing slopes risk being dominated by mosses or tall vegetation. Screening of existing roadside slopes in the region will give local guidance for how the vegetation on slopes with differences in exposure are likely to develop.
- Do not use topsoil or apply fertiliser.
- Do not cover sand or sandy gravel with coarser material.
- Particularly important: Trees should be saved whenever possible. This includes both ecologically valuable trees and trees that constitute a biological cultural heritage, such as pollarded trees.
- The edge between the open road corridor and adjacent forest should preferably be made irregular, both along the road (slightly undulating instead of straight) and transversal to the road (as a gradual ecotone from open land to forest), in order to favour light-dependent shrubs and wide-canopy trees (cf. *Ecotone guidelines*) and their associated biodiversity. Such trees usually do not grow tall and can be favoured at some safe distance from the road. If planting closer to the road, lower species of trees should be chosen, i.e., trees that do not grow tall enough in sun-exposed conditions to risk falling on the road. Such a variation can be combined with differentiated vegetation management, i.e. different management at different distances along the road.
- High and steep slopes are valuable for biodiversity, but slopes should not be built so steep that they are not stable causing the need to prevent erosion by dense vegetation cover or coarse material.
- Consider the possibility to support valuable deposits of the local soil (mainly occurring in the outer slopes) with similar material in road embankments (inner slopes). All new material needs to be documented clean with respect to invasive species.
- Nutrient-rich subsoil may be covered with nutrient-poor substrate suitable for biodiversity. The layer of poor material must be thick enough to prevent deep-rooted herbs and grasses from reaching the rich subsoil. The required thickness will depend on the local flora of potential competitive species, but should never be less than 50 cm.
- Apply large-scale reuse of topsoil only when it does not risk forming a layer of nutrient-rich topsoil that supports high-productivity competitive vegetation. For example, the reuse of thick grass sward should usually be avoided, even if it comes from a species-rich grassland. Instead, use smaller ‘islands’ of such material in order to provide a seed bank and sources of dispersal without risking negative effects of topsoil nutrients.
- If valuable deposits of subsoil, such as sand or calcareous material, need to be removed in the road corridor, this subsoil could be placed in suitable structures elsewhere in the project area, for example on a south-facing slope.

Figure 7.2: A creek restored in connection with a new road in order to create aquatic habitats, e.g. for spawning trout. Överfors, Province of Södermanland, Sweden, 2011.

- In order to create small-scale variation and specific microhabitats for plants and insects and other small animals, consider making uneven surfaces, such as indents in slopes. Scattered piles of stones or logs may also contribute to biodiversity through offering places for shelter or hibernation (larger stones can be partly buried for safety reasons). In flat areas, wet or moist habitats may be constructed, for example permanent waters (ponds), temporary groundwater or runoff water ponds, and wetlands with as permanent soil moisture as possible.
- Where a road crosses water streams, bridge constructions should not obstruct movement of aquatic or terrestrial species belonging to the stream habitat. Since the road building process usually affects the stream, the stream needs to be restored, and there might be possibilities to improve the ecological conditions (Figure 7.2).
- If trap effects are suspected, consider measures for reducing this risk (see *Ecotone guidelines*). For example, resources for vulnerable species could be created away from the traffic, or different habitats could be established on opposite sides of the road to minimise the movement of individuals across the road.

Figure 7.3: Introduction of meadow flora on recently disturbed ground by sowing collected seeds and by placing hay from the meadow on the roadside. Mossby, Province of Närke, Sweden 2020.

Step 3. Establishing vegetation

- If there is a low likelihood of spontaneous establishment of the desired flora, active sowing of the local flora, in particular of target species, should be considered. It can be done e.g., through applying hay with ripe seeds or through sowing, either of seeds collected in the wild or by using local material cultivated in advance for producing larger batches of seeds or plug-plants (Figure 7.3). Spread the desired species over the suitable area of habitat, although not necessarily in high abundance. The plants first established will produce seeds and thereby initiate further establishment of new plants.
- Which plant species are of conservation concern must be determined for each road project, for example through contact with local experts and conservation authorities. Some plant species are themselves endangered and thus constitute conservation targets (Figure 7.4). Some contribute general resources and are always valuable, such as pollen and nectar plants (including trees and shrubs). Other species provide specific resources, for example as food plants for invertebrates. The value of certain plant species for biodiversity may also be site-specific, e.g., if they are host plants for endangered invertebrates that occur in the area.

Figure 7.4: In Sweden, *Gentianella amarella* nowadays occurs mainly in roadside habitats and should be prioritised for introduction in suitable roadsides if it occurs, or previously occurred, in the landscape in question. This northern calcareous roadside habitat hosts many meadow plants, Funäsdalen, Province of Härjedalen, Sweden 2002.

- Never introduce (potentially) invasive species, be it neophytes or native plants. Keep in mind that since new road constructions offer extraordinary conditions for establishment and dispersal of plants, many species may become invasive in roadside habitats even if they show only moderate expansion capacity in other habitats.
- Never plant competitive plant species such as tall fast-growing species or ground-covering species. This means that grasses or other species that form dense vegetation should not be sown. Such species should also be avoided in sections of the road not prioritised for biodiversity measures, in particular in sections close to biodiversity habitats. This is motivated by the risk of dispersal of unwanted competitive species along the road, facilitated by vehicles, cutting equipment and so on.
- Native species are always preferable to alien species. Indigenous species normally host larger numbers of associated organisms, for example plant-eating or pollen- or nectar-eating insects.

- Local plant material is preferable to distant. Locally adapted plants have better chances of surviving, and by using local plants, roadsides can contribute to preserving adaptive genetic diversity.
- In areas where shrubs and trees can be planted without affecting roadside habitats negatively, native species should be chosen, in particular species playing key functions for biodiversity. Examples of species with key functions are species that provide nectar or pollen, that serve as food plant for plant-eating invertebrates or that produce other important resources, such as dead wood, hollow stems etc. Which particular species of trees and shrubs are suitable varies between regions of Europe and should be decided in collaboration with local experts and conservation authorities. Usually, there is sufficient local knowledge about conservation value of different species.

Step 4. Monitoring and evaluation

Since building roadside habitats for biodiversity in a specific case always includes a great deal of trial and innovation, it is desirable to monitor and document the biodiversity effects of the measures in order to learn for the future, to adjust the habitats, adapt management and so on. The monitoring should focus on the aim of the measures, for example the success of sowing.

The presence of invasive species should always be monitored in newly constructed habitats, so that eradication measures can be initiated at an early stage.

7.3 Management of ground and vegetation for biodiversity of conservation concern in roadside habitats

Key results of the review

- ✓ The ecological significance of vegetation management in roadside habitats has been acknowledged and studied, often referring to a resemblance between cut roadsides and managed semi-natural grassland. The significance of ground disturbance and the successional characteristics of roadside vegetation has attracted considerably less attention (but see Riva et al. 2018).
- ✓ The role of an interplay between disturbance and cutting for the vegetation composition and succession in roadsides has hardly been addressed at all.
- ✓ In spite of a relative wealth of studies on roadside cutting and vegetation, rather few studies relate their results to conservation goals or species of conservation concern. Commonly used response variables as species richness can not directly be translated into conservation value.
- ✓ The most commonly studied components of vegetation management are timing and frequency of cutting (once, twice, or more per year), and removal of the cut material.
- ✓ Empirical studies show disparate results regarding all three components. Biodiversity effects of a certain modification of management, for example later cutting or more frequent cutting, vary between studies from positive to neutral and negative. The discrepancies between studies are probably caused by

differences in the vegetation types studied, in particular differences in vegetation productivity.

- ✓ Although there are obvious interaction effects between timing of cutting and frequency of cutting, relationships between those two components have not been systematically evaluated. This is the case also for relationships between frequency of cutting and soil productivity.
- ✓ Mowing for conservation purposes has been studied in meadow habitats, but results and experiences from such studies have rarely been considered in roadside contexts.
- ✓ Although the significance for biodiversity of sparse vegetation and occurrence of bare soil in roadside habitats have been demonstrated in several studies, it has rarely been studied which factors, including ground and vegetation management, that influence the vegetation cover.

Interpretation

- o An ecological design of roadside management should consider both soil/ground and vegetation, and the interactions between those factors. Knowledge about such factors could probably be compiled through interpreting ecological literature from roadside habitats and from other habitats in an applied roadside management perspective. So far this has not been done, and the possibilities of designing management of roadside habitats for biodiversity are therefore somewhat limited by lack of knowledge. However, the literature on roadsides provides a number of indications of management effects on biodiversity that were used in these guidelines.
- o It can be assumed that, following ground disturbance, the vegetation in nutrient-poor or dry conditions reaches a stage of very slow succession, with low and sparse vegetation and good colonisation potential for demanding species from sand habitats, dry meadows, steppe-like habitats etc. There is little need for ground disturbance (to restart succession) and cutting other than to prevent establishment of woody vegetation (Figure 7.5).
- o On more nutrient-rich soils, the succession following ground disturbance go towards tall and species-poor vegetation in which herbs and small plant species are outcompeted mainly by grasses. Here regular cutting is required in order to slow down succession and reduce competition. Mulching accelerates succession towards tall species-poor swards by accumulating nutrient-rich matter in the soil.
    - In high nutrient levels, two or more cuttings per year, combined with removal of the cut material may be needed to keep vegetation and competition low. Such intense cutting, however, restricts the flora and fauna to species that can cope with repeated cutting. Many species of conservation concern can not cope, as indicated by information about red-listed species as well as by studies of meadow ecosystems. High nutrient levels therefore reduce the potentials of maintaining high species richness including demanding grassland species of plants and invertebrates.
    - In moderately high nutrient levels, one cutting event combined with removal of the cut material is enough to keep the vegetation low and to slow down succession. Since more species can cope with a single cutting than repeated cutting, moderately rich soils have better potentials to form

species-rich vegetation and to harbour demanding grassland species compared to richer soils. The timing of cutting is then an important factor.

- It has not been empirically or theoretically evaluated under which nutrient conditions and in which successional stages repeated cutting has desired effects on plant diversity, especially regarding biodiversity (including invertebrates) of conservation concern. This knowledge gap also applies to biomass removal. Much of the needed knowledge could probably be synthesized by using information from other mowing- or grazing-generated habitats. Such a synthesis should be done for different conservation targets, such as demanding plant species of conservation concern, invertebrates, and pollen/nectar resources, including cutting-tolerant nectar plants.
- Effects of repeated cutting imposes positive effects on plant species richness of biomass removal and nutrient depletion, but negative effects on several less disturbance-tolerant organisms. This tradeoff can probably to some extent be reduced through performing cutting when plants and invertebrates are less sensitive, e.g. in the autumn. Suitable cutting schemes can be developed by combining information about soil properties, vegetation structure and composition, and ecology of different species groups, especially tolerance and phenology.
- Cutting and biomass removal on soils with sufficiently low nutrient levels may in the long run create a stable sward similar to semi-natural meadow or pasture habitats. If this is not the case, and the vegetation becomes tall and less species-rich, the succession should probably be restarted, e.g. by scraping off the accumulated organic top layer.
- If scraping is performed for drainiage or other reasons where a diverse flora still remains, measures should be taken to preserve the flora, e.g., by leaving unscraped islands of vegetation, or by re-sowing target species or the entire vegetation. Re-sowing could be done using seeds or hay collected before scraping, or by using smaller portions (not a cover of) of re-used topsoil with seed bank (Figure 7.8).
- In nutrient-poor and dry conditions, some competitive species may still establish, for example tall drought-tolerant grasses. Species richness can be maintained by a cutting regime that hampers these competitors, for example one early cutting (preferably when or slightly before the competitor flowers) with or without removal of hay (depending on productivity, Figure 7.7).
- If invasive plant species establish, vegetation management needs to change focus from favouring habitats and species of conservation concern to mitigation of the invasive. Such mitigation management usually includes intensified and earlier cutting, which disfavours many species of conservation concern. Thus, even if the invasive can be controlled by adapted management, species richness and conservation value of the habitat can be assumed to be strongly reduced by the presence of invasive species.
- Timing of cutting should be adapted to the phenology and cutting tolerance of the vegetation, in particular to target species of conservation concern (Figure 7.6). Examples of how different species groups are favoured by different cutting time are given in the guideline.

Guideline

Identifying sites for adapted management of vegetation and ground

Management should aim at preserving flora and other species groups of conservation concern where they exist, and at developing vegetation and habitats of conservation concern at sites with good potential. Three types of conditions in particular motivate special biodiversity-adapted management:

1. Existing roadside habitats of conservation concern, e.g., by being species-rich, hosting certain target species, or having certain environmental conditions or resources. Here suitable management of vegetation and soil should continue.
2. Roadside habitats that still are species-rich, but that seem to be deteriorating, e.g., through succession towards tall competitive vegetation. The fact that such sites have had better status earlier indicates that the basic environmental conditions are suitable, and that the negative trend may be reversed. Here vegetation management my need to be modified, e.g., by introducing removal of the cut vegetation, or succession be re-started by a top layer removal etc.
3. Species-poor roadsides, predominantly in outer slopes with local soils, where the biodiversity in adjacent habitats indicates high potential for creating or restoring good conditions. A typical example is nutrient-rich topsoil layers on nutrient-poor subsoil such as sand or calcareous material. Here conditions need to be restored, e.g., by removing nutrient-rich top layers.

Frequency of cutting

- Many grassland species of plants and invertebrates of conservation concern do not tolerate more than one cut per season, and roadside habitats with such species should normally be managed with a single cut regime. Roadside habitats may, however, have other conservation values that are less sensitive to, or even dependent of, frequent cutting. One example is pollen and nectar resources provided by cutting-tolerant species such as some clover (*Trifolium*) species.
- Frequent cutting can also be used in combination with removal of the cut material in order to reduce the nutrient levels in nutrient-rich topsoils, thereby favouring more plant species. However, if the nutrient-richness emanates from the local soil, it is not likely that the improved state will persist without continuous intense cutting. Since few species of conservation concern tolerate frequent cutting, this type of site is unlikely to develop persistent vegetation of conservation concern.

Figure 7.5: In very low-productive roadside habitats, cutting is needed only in order to prevent establishment of woody vegetation and can therefore be performed less frequently. Bålsta, Province of Uppland, Sweden 2020*.*

- A second cut, after the vegetation period in autumn, can be considered in medium productive species-rich vegetation in order to remove organic material and reduce litter-forming aftermath. This requires removal of the cut vegetation.
- Cutting less frequently than once per year can be considered for particularly nutrient-poor and dry sites. Many species of plants and invertebrates in such habitats are not adapted to cutting (or grazing), and at very low productivity sites, the vegetation is kept low and sparse without frequent cutting (Figure 7.5).

Removal of the cut material

Removal of the cut material means that the cutting regime is no longer mulching, but more similar to mowing.

Removal should be prioritised mainly in the following situations:

- Roadside habitats that are still species-rich but deteriorating due to increased nutrient levels and competition from tall plant species. The basic conditions should be sufficiently nutrient-poor to host a species-rich vegetation, and the nutrient increase should mainly be due to accumulation of organic matter from the vegetation. In such cases, there is a good chance of reversing the negative trend by reducing the supply of organic matter.
- Roadside habitats in which plant species richness or specific species of plants or other organisms are disfavoured by too thick a layer of plant litter. This situation may occur in habitats rich in plant species from semin-natural hay-meadow and pasture, especially short-lived species which need frequent recruitment from seeds. It may also be the case in habitats rich in ground-digging bees and wasps, or ground-dwelling thermophilic beetles.

These two conditions usually coincide, but there might be situations where the litter layer is a problem without an obvious nutrient increase, for example for digging bees on sandy soils.

Timing of cutting

The timing of cutting is of paramount importance for the reproduction, growth and survival of plants and plant-eating invertebrates that are confined to their host plants. The timing can also be adapted to resemble or complement adjacent habitats, for example a hay meadow, in order to support biodiversity in the landscape.

Figure 7.6: Early cutting next to the road has reduced flower abundance and (most likely) plant species richness compared with later cutting. Alböke, Province of Öland, Sweden 2011.

As a rule, the cutting should be adapted to the reproduction phenology and the tolerance of the occurring species of conservation concern. More specifically, the following criteria may be used:

Late cutting (autumn cutting) can be performed any time after all plants have mature seeds, i.e., also late in the autumn. The cut material should be removed if the vegetation is dense enough to form a litter layer that remains and accumulates from year to year. Late cutting should be applied in:

- Ruderal, early stages of succession. Many ruderal plants show low tolerance to cutting and therefore need to finish reproduction before the cutting. Furthermore, the vegetation cover at early successional stages is low enough not to cause shading problems for smaller species. Habitats suitable for this cutting regime are characterized by annual ruderals or arable weeds (e.g.

Papaver & *Delphinium*), and perennial ruderals with low tolerance to cutting (species rarely found in grazed or mown grasslands).
- Dry or very nutrient-poor roadside habitats. Plants in such habitats are adapted to stress (drought) rather than to disturbance (cutting, grazing etc.). Also, here, shading of smaller species is low. Such roadside habitats harbour species from a wide range of drought-stressed habitats across Europe. Removal of the cut material is normally not needed.
- Sites with certain species of plants or invertebrates of conservation concern that depend on an undisturbed summer. Habitats and sites suitable for this cutting regime can be identified in collaboration with local experts and conservation authorities.
- Sites where a summer flower resource for pollinators is prioritised.

Late summer cutting is performed after most plants have mature seeds, but no later than that, in order not to cause unnecessary shading of small plant species, plant life stages, ground invertebrates etc, and to avoid resource accumulation in storage organs of competitive species. Late summer cutting should be applied in:
- Most types of species-rich roadside vegetation with species from semi-natural grassland habitats (unfertilised pastrures and hay meadows), except for those where late (above) and early cutting (below) is recommended (Figure 7.6). This cutting regime is thus suitable for later successional stages in nutrient-poor conditions. The vegetation is productive and dense enough to require removal of the cut material to persist.
- Roadsides with species from spring- and early summer-flowering habitats. Examples of source habitats for such species are summer-dry Mediterranean or rocky habitats in which plants utilise the wetter spring season for reproduction, and deciduous forest habitats in which plants utilise the period before the trees come into leaf. Removal of the cut material is not needed if the vegetation is low and sparse enough not to accumulate litter. In low-productive habitats with low competition, cutting may be performed as autumn-cutting (previous point).

Early cutting is performed well before the peak of flowering of the vegetation. An early cutting triggers regrowth and re-flowering of many grassland plant species that have evolved tolerance to grazing. Usually, those plants tolerate only one cutting before reproduction in order to set seeds. The cut material should be removed if the vegetation is dense enough to form a litter layer that remains and accumulates from year to year. Early cutting should be applied in:
- Habitats with a flora of re-flowering (grazing-tolerant) grassland plants, where a later cutting risks disfavouring small species, life stages, ground invertebrates etc. One example is ruderal vegetation on well drained soils with a mixture of tall pioneers (e.g., *Cicorium*, *Daucus*, *Melilotus*) and small low-competitive species (e.g., *Herniaria*, *Linum catharticum*). If no such sensitive species are present, tolerant species may well be cut later as late summer cutting.
- Sites where a late-summer flower resource would favour pollinators, and where cutting-tolerant, re-flowering plants are present (e.g., *Trifolium* and the tall

pioneers in the previous point). In order to extend the flower resource over the season, a mix of early- and late-mown sites is favourable.

- Species-rich sites where a competitive plant species needs to be suppressed by early cutting (Figure 7.7).

Figure 7.7: Early cutting next to the road has increased plant species richness by suppressing competitive grasses, here *Arrenatherum elatius*, compared with later cutting. Alböke, Province of Öland, Sweden 2010.

<u>Ground disturbance to restart succession</u>

Ground disturbance for biodiversity purposes usually refers to removal of a top layer of soil, rich in nutrients and organic matter. It can be organic matter that has accumulated over time, in particular where mulching has been performed, or top layers of original soils. Ground disturbance serves to restart succession and reduce nutrient levels through removal of nutrient rich topsoil or a dense vegetation cover. This measure is relevant in the following situations:

- Roadsides that have previously been rich in species of grassland plants and still contain high conservation values, but which seem to be deteriorating through succession towards tall, competitive vegetation, in spite of cutting and removal of the cut vegetation (see removal above and Figure 7.8).

- Roadsides that have previously been rich in species of ruderal or dry meadow plants and still contain high conservation values, but which seem to be deteriorating through succession towards dense, covering (but not necessarily tall) vegetation of a few grass species
- Species-poor roadsides, predominantly on outer slopes with local subsoils, where the following criteria indicate high potential for creating or restoring good conditions:
    - Rich flora or fauna in adjacent habitats that can be expected to colonise the roadside.
    - Favourable nutrient-poor subsoil such as sand or calcareous material.
    - Biodiversity in the roadside suffers from a nutrient-rich topsoil layer, accumulated over time, or added when the road was built.

<u>Adaptation of ground disturbance that is performed for road maintenance purposes</u>

- Roadside habitats are regularly subjected to a number of ground disturbances such as grading and ditching to improve water runoff and drainage. Normally, the entire surface is treated, but at sites prioritised for biodiversity, it is recommended to modify the treatment in order not to erase the existing biodiversity of conservation concern. This applies to both species-rich vegetation and to occurrences of certain species of plants and insects.
- In some cases, species of conservation concern may be preserved by adjusting the timing of the disturbance to a period where the species in question is not present in the roadside habitat.
- In order to preserve vegetation, surface removal needs to be done gradually, while saving islands of undisturbed vegetation at regular intervals along the roadside. These islands are removed later once they have dispersed their species to the scraped surfaces (Figure 7.8). Small populations of plant species of conservation concern, colonies of digging bees, wasps etc. can in many cases, be saved entirely without jeopardising the function of the road construction.

Figure 7.8: Over a number of years, a layer of more or less nutrient-rich organic topsoil builds up on the nutrient-poor road construction material. Competitive species become more and more dominant, and the topsoil layer compromises the drainage of the road. If the vegetation is still rich in species of conservation concern, patches of vegetation can be saved when scraping off the top layer, as dispersal cores for re-establishment of species. Knivsta, Province of Uppland, Sweden 2020.

7.4 Construction and management of roadside habitats in a landscape perspective

Key results of the review

- ✓ Roads and their habitats cut through almost every type of landscape in Europe, although they are most common in centres of urbanisation in the lowlands.
- ✓ The influence of roadside habitats on the diversity and abundance of the local species, including species of conservation concern, varies from positive (Zielinska et al. 2016) to neutral and negative (Bernes et al. 2017) depending on the interaction between landscape type (mainly the landscape's habitat configuration) and roadside type.
- ✓ One of the major explanations for roads contributing to biodiversity conservation is that some roads provide habitats for essential resources and reproduction for

species of conservation concern in the surrounding landscape. This often implies that roadsides harbour species from historically richer landscapes and land-use forms.

- ✓ Although there are several indications of roads serving as dispersal corridors or stepping-stones (e.g., Munguira & Thomas 1992), empirical studies are ecologically and geographically diverse and show diverging results. There is thus little information about the factors in the roadside and landscape that contribute to dispersal functions of roadsides, the species groups favoured and possible dispersal rates and distances.
- ✓ Direct evidence of roadsides contributing to green infrastructure is provided by the actual occurrence of reproducing populations or foraging individuals in roadside habitats. This contributes to a denser pattern of species distributions and creates a potential for dispersal along the road.
- ✓ Adjacent habitats sometimes strongly influence the local conditions in the roadside habitat in a negative way, e.g., through shading and leaf litter (adjacent forest) or fertilisation and biocides (adjacent arable fields).

<u>Interpretation</u>

- o The ecological similarity between the roadside habitats and the habitats in the surrounding landscape is of paramount importance for a road's impact on local and regional biodiversity, including its contribution to conservation (cf. *Landscape guidelines*).
- o In open or previously open landscapes where many species depend on the type of habitats that occur along roads, roadsides may increase the availability of important habitats and resources, thereby favouring landscape biodiversity.
- o In other landscapes, for example forested landscapes, open roadside habitats are less likely to offer habitats for the local (forest) flora and fauna. In such cases, total biodiversity may increase, but without favouring the landscape's species. Roadside habitats may even pose threats by introducing invasive alien species (Rauschert et al. 2017).
- o In many landscapes, roadside habitats mimic or preserve historical habitats that have disappeared in the surroundings due to changed and intensified land use. Roadside habitats thereby constitute a biological cultural heritage, which may be important for conservation. This implies that roadside habitats may be important for conservation despite being ecologically different from the current surrounding habitats. In such cases, roadside habitats may constitute biodiversity hotspots similar to various remnant semi-natural or natural habitats (Figure 7.9).
- o The roadside habitats may have important functions as corridors or stepping stones for species, for example for open-landscape species through abandoned and overgrown landscapes. The most important factors supporting this dispersal function are that roads provide either habitats for reproduction and multi-generation dispersal, or important resources such as flower resources that are used by pollinators along the road. Another factor is increased dispersal by vehicles or roadside management equipment. Other than thus making roadside habitats as suitable as possible for biodiversity, there is not sufficient knowledge for recommending measures for how and where to make roadsides conduits for dispersal.

- Because of negative effects of some types of adjacent habitats and land-use forms, many stretches of roadsides cannot be expected to be important for biodiversity. This is especially the case for habitats exposed to fertiliser and pesticides from adjacent arable fields. Forest may restrict roadside biodiversity through shading, where the long-term effect depends on the longevity of the forest stand. Open-land species in the roadside may expand following cutting of the forest.
- Conversely, roadsides through biodiversity-rich landscapes, e.g. nature reserves, may show higher biodiversity.
- Importantly, far from all species groups in a landscape can be favoured by roadsides. This implies that a new road may eradicate habitats, ecological resources and species of conservation concern without offering any alternative roadside habitats.
- Roadside habitats and their species are frequently discussed in a biodiversity conservation context, but analysis is required on the extent to which roadsides can also contribute to the conservation of cultural heritage, by harbouring biological cultural heritage from past landscapes, ecosystems, and land-use forms.
- Historical land-use in the original habitats of species may inform roadside management, e.g., in terms of timing of vegetation cutting and type and frequency of ground disturbance.

Guideline

When a road corridor through a landscape is decided, three criteria in particular should be considered when assessing the net effect of the road on biodiversity conservation:

(1) Habitats and populations in the road corridor that will be *erased* without any possibilities of creating new similar habitats along the roadsides.
(2) Habitats and populations next to the road corridor or in the landscape that risk being critically *disturbed* by the road, e.g., through contaminants, noise, light, collision risk (including ecological trap effects) or barrier effects.
(3) Habitats and populations in the road corridor or in the surrounding landscape that have the *potential to be favoured* by the road, through the building and maintenance of suitable roadside habitats.

The following part of this guideline addresses point (3). It thus focusses on making a roadside as beneficial as possible for biodiversity once the decision is taken where to build the road, or if a road is already existing. In brief, we propose a workflow of seven steps, which are described in detail below:

1. Identify and map biodiversity of conservation concern in the landscape around the road.
2. Identify which biodiversity may be favoured by roadside habitats and map where along the road suitable habitats occur or may be created (matching landscape species pool with roadside potentials).
3. Assess and map colonisation potential for the roadside habitats.
4. Assess and map potential ecological traps.
5. Prioritize and plan where to create which habitats.
6. Create the planned roadside habitats based on best practice.

7. Plan future management of the habitats.

Step 1. Identifying landscape biodiversity of conservation concern

I. Screen the surrounding landscape (and the road corridor) for species of conservation concern, in particular:

A. Species groups that are known to or expected to be favoured by roadside habitats. Typically, roads can favour species belonging to grassland habitats, dry habitats, sandy habitats, ruderal habitats, and semi-open or egde habitats with light-influenced schrubs and trees, including avenues and hedges. Locally, also several other roadside habitats may be formed that can support certain species groups, for example species from various shore habitats, rock habitats, karst or alvar habitats, and wetlands.

B. Declining species groups and habitats. In many cases, such target populations and habitats constitute a legacy of past landscape conditions, either human-made (e.g., from pre-industrial agriculture) or natural. They may be found as:

b. Intact habitat patches that are still ecologically functional, for example grazed semi-natural pasture or some large enough patches of natural or near-natural habitat.

c. Less ecologically functional remnant patches of habitat from earlier landscapes, either human-made habitats (e.g., abandoned semi-natural grassland) or natural (small patches of steppe or scrubland).

d. Remnant populations of plants and invertebrates that still occur in deteriorating habitats, for example grassland plants in overgrown habitats and ground-digging hymenoptera in the last open-ground spot in an overgrowing habitat.

Which are the actual species and habitats that are of conservation concern varies between countries and regions depending on landscape and conservation policy. Typically, conservation concern applies to e.g., nationally red-listed species, species subject to European conservation schemes, and species with ecological key functions, such as important host plants for invertebrates, nectar, or pollen plants etc.

II. Screen the surrounding landscape for core sites for biodiversity, having a potential to become connected by high-value roadsides. This would in particular concern various types of grassland (in a wide sense), ruderal habitats and edge habitats, i.e., habitats that are similar to the roadside habitats in terms of resources, microhabitats and so on.

Step 2. Which species in the landscape may be favoured by roadside habitats?

Estimate the possible ecological matches between (A) the identified species' habitat demands and (B) the potential habitats that can be constructed along the (new) road. This process needs the involvement of biologists.

A. Regarding species' demands, complement the list of species identified in step 1 with habitat demands for each species, based on expert assessments, species data sheets, literature searches etc. Knowledge about species' ecology (which usually not consider roadside contexts) needs to be combined with knowledge about roadside habitats.
B. The construction of potential habitats is treated in **Feil! Fant ikke referansekilden.**. It may be useful to consider potential habitats in three steps:
    a. Roadside habitats that will be constructed, given the planned architecture of the road.
    b. Roadside habitats that can easily be constructed using slight modification of the original plan for the road, for example by avoiding top-soiling and by choosing type and location of ornamental plants.
    c. Roadside habitats that require more substantial alteration of the original road plan, e.g., less steep embankment slopes or the construction of larger areas of specific habitats for biodiversity.

Figure 7.9: Roads running through active semi-natural pastures may harbour a large proportion of the pasture biodiversity (top, Alleghe, Province of Belluno, Italy). When management ceases and the landscape is overgrown, much of the pasture flora may remain in the roadside habitat (bottom, Böda, Province of Öland, Sweden).

Fig. 7.10: Much of the European steppes have been transformed into arable land. The roadside habitat has many ecological processes and conditions in common with the steppe and provides refugia for some steppe species. Babadag, Province of Dobrogea, Romania 2004.

The identification of potential roadside habitats should be done both qualitatively (*which habitats can be created?*) and spatially (make a map of *where different habitats can be created*, given geo-topography etc.). This enables quantitative description of the potential area and distribution of different roadside habitats in terms of *total area, average area of single habitat patches,* and *distances between patches,* all being essential for the conservation status of the species in the habitats. Distances between patches enables analysis of the *connectivity of roadside habitat patches*, i.e., of the potential for dispersal between patches along the road, and between roadside habitats and the surrounding habitats.

The match between a species and a potential roadside habitat can be described using a four-degree scale, based on likely population viability once the species has reached the roadside habitat:

I. High match – the species is likely to establish a viable population in the roadside habitat.
II. Potential high match, but uncertain assessment due to data deficiency.
III. Moderate match – the species is less likely to establish a viable population in the roadside habitat.
IV. Low match – the species is not likely to establish a viable population in the roadside habitat (the roadside habitat does not fit the species).

Step 3. Assessment of colonisation potential of the roadside habitats

Estimate the spatial matches between the occurrences of species (and habitats) of conservation concern (from step 1) and the potential roadside habitats (from step 2), in order to estimate the likelihood of spontaneous dispersal to the new roadside habitats. For most species of vascular plants, such dispersal is likely only over very short distances, and thus mostly from dispersal cores located in more or less direct connection with the roadside habitats. Flying insects such as bees and butterflies may colonise the roadside habitats from at least a couple of hundred metres, often further, while less mobile insects, e.g., grasshoppers and ground beetles, have intermediate dispersal capacity. For occurrences of species outside the expected dispersal distance, facilitated colonisation by sowing, planting or other kind of introduction is necessary (see 7.2).

Step 4. Assessment of ecological traps

Estimate whether an ecological trap risks being created in certain stretches of the road, through the construction of certain roadside habitats (see *Ecotone guidelines)*. A roadside habitat-related trap effect implies that the habitat attracts individuals of a species, which face such poor success in the roadside that the net effect on the species in the landscape is negative. In order to minimise the risk of creating an ecological trap, estimate whether some roadside habitats should be avoided along some stretches of the road, or whether special measures for mitigating the trap effect should be taken.

Step 5. Summarising prioritisation

Finally, make a summarising prioritisation and plan (A) where to construct which habitats and (B) how to ensure that the new habitats are colonised by species of conservation concern. For the choice of type and localisation of constructed roadside habitats, the following general classes and criteria for potential species richness and colonisation may be useful. It should be noted, however, that criteria for prioritisation must always be locally adapted, for example to the general aims for biodiversity and conservation in the road project in question, and to the type of biodiversity threatened by the road and in the landscape in general

A. Chances of high species richness in roadside habitats.

I. Highest priority: *large areas* of important roadside habitats can be built in landscapes that have *many occurrences* of species of conservation concern, located *close to the road* (large potential of both landscape and road).
II. High priority: *Smaller areas* of important roadside habitats can be built in landscapes that have *many occurrences* of species of conservation concern, located *close to the road* (large landscape potential).
OR:
Large areas of important roadside habitats can be built in landscapes that have *fewer occurrences* of species of conservation concern, located *less close to the road* (large road potential).
III. Low priority: *Smaller areas* of important roadside habitats can be built in landscapes that have *few occurrences* of species of conservation concern, located *close to the road* (poorer landscape and road potential, but good dispersal potential).
IV. Lowest priority: *Smaller areas* of important roadside habitats can be built in landscapes that have *few occurrences* of species of conservation concern, located *less close to the road* (poorer potential of landscape, road and dispersal).

B. Chances of colonisation
In the establishment of species of conservation concern in the new roadside habitats, the chances of spontaneous colonisation depend on distance and group of organisms. Little is known about dispersal capacity of different species in different conditions, and the following classes and criteria represent a pragmatic and rather coarse classification of dispersal capacity. Local more specific information may be used for more precise estimates in certain cases.
I. High chance of spontaneous colonisation: Core habitats in the landscape are situated directly adjacent to the roadside habitat (vascular plants), or <200 m (less mobile invertebrates) or <500 m (mobile invertebrates) from the roadside habitat.
II. Intermediate chance of colonisation: Core habitats in the landscape are situated <50 m (vascular plants), <500 m (less mobile invertebrates) or <1 km (mobile invertebrates) from the roadside habitat.
III. Low chance of colonisation: Core habitats in the landscape are situated >50 m (vascular plants), >500 m (less mobile invertebrates) or >1 km (mobile invertebrates) from the roadside habitat.

For class III, facilitation of colonisation is necessary, and can be achieved by sowing, planting or other transfer of diaspores or individuals to the roadside habitat.

Step 6. <u>Construction of roadside habitats and measures for establishment of species</u>.
See 7.2

Step 7. <u>Future management</u>

In future management of the new roadside habitats and in management of existing roadside habitats, the landscape perspective should be taken into account especially in the following ways:

a. When road biodiversity is a legacy of past landscapes (Chaudron et al. 2018), or for other reasons is more or less confined to roadside habitats, it is important not to perform ditching, grading, reconstruction, or restarting of vegetation for biodiversity purposes in a way that erases the vegetation and habitats for species. If the populations become extinct in roadsides, there is little chance that the species will re-colonise from the surroundings. In such cases, any intensive management intervention needs to be done gradually to allow new exposed ground to be recolonised from spared dispersal cores before the spared sections are treated. For rare species that occur scattered along the road, the actual occurrences may need to be mapped prior to the intervention, in order to make sure that a proportion (mostly for rare species) of those species are spared. Some habitats and populations, e.g., colonies of rare ground-digging bees and wasps, and particularly threatened species, may need to be saved entirely through all steps of the management intervention.
b. In such landscapes, i.e., where roadsides harbour considerable proportions of the landscape biodiversity, and especially if species of high conservation concern occur in the roadside, it is particularly important to find the best possible methods for vegetation management, in order to strengthen population viability.
c. Where roadside habitats occur near important habitats in the landscape and a trap effect is unlikely, roadside management should aim at creating vegetation and ground structures that are as similar as possible to the neighbouring habitat, in order to create a supporting habitat in the roadside. For example, the timing of vegetation cutting could be adapted to a neighbouring hay meadow, and the frequency and type of ground disturbance to a neighbouring sand dune system. Highly varying (between years) management reduces the chances of creating such similarities and favours mainly generalist species.

<u>Preparing for coming projects</u>

For smooth handling of roadside habitats in a landscape perspective, road managers in collaboration with biologists and conservation actors should prepare regional lists of species of conservation concern that are, or have a great potential to be, favoured by roadside habitats, and, if possible, the type of habitats concerned. Conservation concern here refers to nationally red-listed or legally protected species, species subject to European conservation schemes, species with ecological key functions etc. Criteria for listing are, for example:

a. Species regularly occurring in roadside habitats.
b. Species rare in roadside habitats, but that seem to have highly viable populations when occurring in such habitats.
c. Species having a large proportion of their populations in roadside habitats (roadsides are thus highly important for the conservation status of the species in the region in question).

Such a list should be communicated with planners and relevant performers (including landscape architects and designers) at early stages of road construction projects.

8 Synthesis

Roads have negative impacts on biodiversity and ecological functions across spatial scales, but also have a great potential for positive effects. For road projects to contribute to regional, national and EU biodiversity targets, e.g., the EU 2030 Biodiversity Strategy regarding increased connectivity, knowledge on how to reduce negative road impacts and to realise benefits, needs to be implemented in roadside planning, construction, and management. Thus, combined systematic and narrative reviews synthesize current knowledge about ecological impacts of roads across spatial scales. The key findings of these reviews are then structured and interpreted in a set of guidelines. The overall approach is to identify risks and specific challenges and to evaluate the potentials for roadside to contribute to ecological processes in the landscape. These possibilities are then further explored by matching possible roadside features with information on habitats and species in the surrounding landscape, combined with an evaluation of potential ecological trap effects.

- The *Landscape guidelines* provide a stepwise procedure to identify risks and potentials in the landscape based on geology, climate, and local abiotic and biotic conditions. Seven major road impacts (road-kills, habitat fragmentation, biological invasions, light pollution, noise pollution, chemical pollution, and hydrogeological alterations) are addressed and measures to reduce the impact of these are addressed for specific landscape settings.

- The *Ecotone guidelines* address how gradients along and across the roadside contribute structures and resources for biodiversity, and how they relate to habitat quality and landscape composition and configuration. Strategies to reduce potential ecological trap effects through clever design of roadside habitats are essential. Guidelines point out the importance of the width and height of the roadsides to be able to locate resources away from traffic and prevent roadkill, as well as continuity along the road, but not across roads.

- The *Habitat guidelines* provide solutions on how to overcome constraints and to realise the potentials in the landscape by creating and maintaining roadsides that function as high-quality habitats and as corridors for dispersal. The respective guidelines highlight soil characteristics, exposure, local species pools and dispersal limitations as critical for roadside construction, but also measures to maintain heterogeneity and sufficient length of roadside stretches targeted for biodiversity. Management regimes to prevent competitive exclusion of species and maintain ecological functions over time are critical and have to be adjusted to bedrock, soil, climate, and vegetation. Guidelines also help in identifying sections of road with higher potential for biodiversity and in providing prioritisation based on both site and landscape context. This includes the importance of historic legacy and conservation concerns.

Key messages

- Prioritise allocation of resources to promote habitat quality where the landscape setting, soil qualities, exposure, and sufficient slope and width of the roadsides allow viable populations, and potentially function as corridors for dispersal with low risks of ecological traps.
- Identify potentials and limitations in the landscape and use the habitat and ecotone guidelines to integrate solutions across scales to accommodate habitat quality, continuity and potentially connectivity.
- Provide continuity in structures and management of roadsides over time and space, this includes structural connectivity.
  - The evidence for the function of roadsides as dispersal corridors is weak, so the best approach for landscape connectivity would be to make roadsides as good as possible for biodiversity and take measures to prevent invasive species using the same structures for dispersal.
- Overall, the guidelines provide key rules and practical solutions to improve biodiversity and ecological functions in roadsides. The guidelines have to be translated into local action, as the local context and prioritisations have to be included in strategy development, planning, construction, and operation.

9 Acknowledgements

The research presented in this report was carried out as part of the CEDR Transnational Road Research Programme Call 2016. The funding for the research was provided by the national road administrations of Austria, Germany, Ireland, Netherlands, Norway, Slovenia, and Sweden.

10 References

Reports and output from the EPICroads project

Hanslin HM, Kollmann J, Kroeger SB, Uhe L, Behrendt S, Wissman J, Lennartsson T, Habel JC, D'Amico M, Hovstad KA. 2019. Ecological effects of roads – a review of the literature, Report CEDR Transnational Road Research Programme.

Lennartsson T, Axelsson-Linkowski W, Westin A, Wissman J, D'Amico M, Kollmann J, Uhe L, Kroeger SB, Hanslin HM. 2021. Roadside habitats and biodiversity. A literature review with focus on vascular plants and insects. Report CEDR Transnational Road Research Programme.

Fischer C et al. High-value roadsides contribute to habitat connectivity in contrasting landscapes: A case study on modelling structural and functional connectivity. Under review

Kollmann J et al. Development of a classification system that evaluates roadside habitats in Europe. CEDR Report

Kollmann J et al. Roadsides as novel ecosystems and potential ecological traps: reviewing the state of knowledge. Chapter in: Road Ecology: synthesis and perspectives", D'Amico M, Barrientos R and Ascensao F (eds.) Springer. Under review

Kroeger SB et al. Impacts of roads on bird species richness: A metaanalysis considering road types, habitats and feeding guilds. Under review

Other scientific references

Bernes C, Bullock JM, Jakobsson S, Rundlöf M, Verheyen K, Lindborg R. 2017. How are biodiversity and dispersal of species affected by the management of roadsides? Environmental Evidence 6:24.

Biglin K, Dupigny-Giroux L-A. 2006. Mapping the road-effect zone to assess impacts of proposed road segments. Journal of Conservation Planning 2: 1—16

Broniewicz E, Ogrodnik K. 2020. Multi-criteria analysis of transport infrastructure projects. Transportation Research Part D: Transport and Environment 83: 102351

Bucharova A, Bossdorf O, Hölzel N, Kollmann J, Prasse R, Durka W. 2019. Mix and match: regional admixture provenancing strikes a balance among different seed-sourcing strategies for ecological restoration. Conservation Genetics, 20: 7-17.

Chaudron C, Perronne R, Bonthoux S, Di Pietro F. 2018. A stronger influence of past rather than present landscape structure on present plant species richness of road-field boundaries. Acta Oecologica 92: 85–94.

Clark CM, Tilman D. 2008. Loss of plant species after chronic low-level nitrogen deposition to prairie grasslands. Nature 451:712–715.

Deguise I, Richardson JS. 2009. Movement behaviour of adult western toads in a fragmented, forest landscape. Canadian Journal of Zoology, 87: 1184-1194.

Fekete R, Nagy T, Bódis J, Biró É, Löki V, Süveges K, ... Molnár A. 2017. Roadside verges as habitats for endangered lizard-orchids (Himantoglossum spp.): Ecological traps or refuges? Science of the Total Environment, 607: 1001-1008.

Figueiredo L, Krauss J, Steffan-Dewenter I, Cabral JS. 2019. Understanding extinction debts: spatio–temporal scales, mechanisms and a roadmap for future research. Ecography 42: 1973–1990.

Forman RTT, Alexander LE. 1998. Roads and their major ecological effects. Ann. Rev. Ecol. Syst. 29:207-31

Forman RTT, Baudry J. 1984. Hedgerows and hedgerow networks in landscape ecology. Environmental Management 8: 495–510.

Gann GD, McDonald T, Walder B, Aronson J, Nelson CR, Jonson J, Hallett JG, Eisenberg C, Guariguata MR, Liu J, Hua F, Echeverría C, Gonzales E, Shaw N, Decleer K, Dixon KW. 2019. International principles and standards for the practice of ecological restoration. Second edition. Restoration Ecology, 27: S1–S46.

Garmendia E, Apostolopoulou E, Adams WM, Bormpoudakis D. 2016. Biodiversity and Green Infrastructure in Europe: Boundary object or ecological trap? Land Use Policy, 56:315-319.

Gustafsson L, Hansson L. 1997. Corridors as a Conservation Tool. Ecological Bulletins 46: 182–190.

Homyack JA, O'Bryan CJ, Thornton JE, Baldwin RF. 2014. Anuran assemblages associated with roadside ditches in a managed pine landscape. Forest Ecology and Management, 334: 217-231.

IPBES (2019): Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. E. S. Brondizio, J. Settele, S. Díaz, and H. T. Ngo (editors). IPBES secretariat, Bonn, Germany.

Jakobsson S, Bernes C, Bullock JM, Verheyen K, Lindborg R. 2018. How does roadside vegetation management affect the diversity of vascular plants and invertebrates? A systematic review. Environmental Evidence 7: 17.

Kallioniemi E, Åström J, Rusch GM, Dahle S, Åström S, Gjershaug JO. 2017. Local resources, linear elements and mass-flowering crops determine bumblebee occurrences in moderately intensified farmlands. Agriculture, Ecosystems & Environment 239: 90-100.

Keilsohn W, Narango DL, Tallamy DW. 2018. Roadside habitat impacts insect traffic mortality. Journal of Insect Conservation 22: 183-188.

Le Viol I, Jiguet F, Machon N, Scher O, Kerbiriou C. 2015. Road network in an agrarian landscape: Potential habitat, corridor, or barrier for small mammals? Acta Oecologica 62: 58-65.

Ledda A, De Montis A. 2019. Infrastructural landscape fragmentation versus occlusion: A sensitivity analysis. Land Use Policy 83: 523-531

McDougall KL, Lembrechts J, Rew LJ, Haider S, Cavieres LA, Kueffer C, ... , Alexander JM. 2018. Running off the road: roadside non-native plants invading mountain vegetation. Biological Invasions 20: 3461-3473.

Meek R. 2014. Temporal distributions, habitat associations and behaviour of the green lizard (Lacerta bilineata) and wall lizard (*Podarcis muralis*) on roads in a fragmented landscape in Western France. Acta Herpetologica 9: 179-186.

Milton SJ, Dean WRJ, Sielecki LE, van der Ree R. 2015. The function and management of roadside vegetation. Van der Ree R. Handbook of Road Ecology, Willey & Sons Ltd, 373-381.

Müllerová J, Vítková M, Vítek O. 2011. The impacts of road and walking trails upon adjacent vegetation: Effects of road building materials on species composition in a nutrient-poor environment. Science of the total environment 409: 3839-3849.

Munguira ML, Thomas JA. 1992. Use of road verges by butterfly and burnet populations, and the effects of roads on adult dispersal and mortality. Journal of Applied Ecology 29: 316-329.

Noordijk J, Delille K, Schaffers AP, Sýkora KV. 2009. Optimizing grassland management for flower-visiting insects in roadside verges. Biological Conservation 142: 2097-2103.

Noordijk J, Schaffers AP, Heijerman T, Boer P, Gleichman M, Sýkora KV. 2010. Effects of vegetation management by mowing on ground-dwelling arthropods. Ecological Engineering 36: 740-750.

Oleksa A, Gawroński R, Tofilski A. 2013. Rural avenues as a refuge for feral honeybee population. Journal of Insect Conservation 17: 465–472

Oleksa A, Gawroński R, Ulrich W. 2009. Association of *Ovalisia rutilans* (Fabricius, 1777) (Coleoptera: Buprestidae) with thermophilous habitats toward its range edge in northern Poland. Baltic Journal of Coleopterology 9: 39-44.

O'Sullivan OS, Holt AR, Warren PH, Evans KL. 2017. Optimising UK urban road verge contributions to biodiversity and ecosystem services with cost-effective management. Journal of environmental management, 191: 162-171.

Phillips BB, Bullock JM, Osborne JL, Gaston KJ. 2020. Ecosystem service provision by road verges. Journal of applied ecology 57:488-501.

Planillo A, Kramer-Schadt S, Malo JE. 2015. Transport infrastructure shapes foraging habitat in a raptor community. PLoS One, 10(3), e0118604.

Ouédraogo DY, Villemey A, Vanpeene S. et al. 2020. Can linear transportation infrastructure verges constitute a habitat and/or a corridor for vertebrates in temperate ecosystems? A systematic review. Environ Evid 9:13.

Rauschert ESJ, Mortensen DA, Bloser SM. 2017. Human-mediated dispersal via rural road maintenance can move invasive propagules. Biological Invasions 19: 2047–2058

Reijnen R, Foppen R. 1994. The effects of car traffic on breeding bird populations in woodland. I. Evidence of reduced habitat quality for willow warblers (Phylloscopus trochilus) breeding close to a highway. Journal of Applied ecology, 31: 85-94.

Richter EG, McKnight KB. 2014. Ecology of northeastern roadside mosses. Journal of the Torrey Botanical Society 141: 250-264.

Riva F, Acorn JH, Nielsen SE. 2018. Localized disturbances from oil sands developments increase butterfly diversity and abundance in Alberta's boreal forests. Biological Conservation 217:173–180

Roberts K, Sjolund A. 2015. Incorporating biodiversity issues into road design: The road agency perspective, IN R van der Ree, DJ. Smith, C Grilo. Handbook of Road Ecology, ISBN: 978-1-118-56818-7 April 2015 Wiley-Blackwell 552 Pages pp 27-32.

Rosell C, Torrellas M, Colomer J, Reck H, Navàs F & Bil M. 2000. Maintenance of ecological assets on transport linear infrastructure. Wildlife & Traffic, A European Handbook for Identifying Conflicts and Designing Solutions. CEDR Report.

Shilling FM, Waetjen DP. 2012. The road effect zone GIS model Report. Sustainable Transportation Center, University of California Davis

Steinfeld D, Kern J, Gallant G, Riley S. 2011. Monitoring roadside revegetation projects. Native Plants Journal 12: 269-275.

Sydenham MAK, Eldegard K, Totland Ø. 2014. Spatio-temporal variation in species assemblages in field edges: seasonally distinct responses of solitary bees to local habitat characteristics and landscape conditions. Biodiversity and Conservation 23: 2393–2414.

Villemey A, Jeusset A, Vargac M, Bertheau Y, Coulon A, Touroult J, Vanpeene S, Castagneyrol B, Jactel H, Witte I, Deniaud N, De Lachapelle FF, Jaslier E, Roy V, Guinard E, Le Mitouard E, Rauel V, Sordello R. 2018. Can linear transportation infrastructure verges constitute a habitat and/or a corridor for insects in temperate landscapes? A systematic review. Environmental Evidence 7:5.

White PS. 1979. Pattern, process, and natural disturbance in vegetation. The Botanical Review 44:229-299.

Wrzesień M, Denisow B. 2016. Distribution and abundance of bee forage flora across an agricultural landscape – railway embankments vs. road verges. Acta Societatis Botanicorum Poloniae 85: DOI: 10.5586/asbp.3509.

Wubs EJ, Van der Putten WH, Bosch M, Bezemer TM. 2016. Soil inoculation steers restoration of terrestrial ecosystems. Nature plants, 2: 1-5.

Zielinska KM, Kiedrzynski M, Grzyl A, Rewicz A. 2016. Forest roadsides harbour less competitive habitats for a relict mountain plant (*Pulsatilla vernalis*) in lowlands. Scientific reports 6: 31913.

Zielinska KM, Misztal M, Zielnska A, Zywiec M. 2013. Influence of ditches on plant species diversity in the managed forests of Central Poland. Baltic Forestry 19: 270-279.

Annex 1: Glossary

Biodiversity, or biological diversity. The Convention on Biological diversity definition is the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems.

Biological invasions - Markedly increased dispersal, distribution and abundance of non-native species (neobiota: e.g., cheatgrass, giant hogweed, Alaska lupin), often facilitated by human activities and with negative effects on biodiversity and ecosystem services. Some native species show similar trends (bracken, gorse, reed). These (plant) species are often more common along roads, because of effective dispersal with vehicles and frequent irregular disturbance.

Chemical pollution - Anthropogenic introduction of contaminants into the natural environment.

Coenocline - Spatial sequence of plant, animal, or fungal communities along an environmental gradient ('ecocline'), as often seen at roadsides.

Complex habitat requirements - Some species, e.g., many lepidoptera, need different habitats for larval and adult life stages. The corresponding mosaic of habitat types can occur along roads.

Contact vegetation - Adjacent community types at ecological gradients, e.g., woodland and grassland.

Dispersal corridor - Geographical space including suitable habitat connecting wildlife or plant populations separated by human activities or infrastructures.

Ecological corridor - Geographical space connecting well-preserved areas and related ecological processes.

Ecological function - Ecological processes that are facilitated by biodiversity, e.g., carbon sequestration, nitrification and pollination. These functions are often modified by roads.

Ecological novelty - This can be caused by invasive alien species and/or fundamental changes in ecological processes beyond resilience of an ecosystem. The resulting novel ecosystems (e.g., at roadsides) have some ecological value and are self-regulating but cannot be restored towards the original ecosystems.

Ecological trap - Sites with high attraction for some species because of locally high resource availability, but low fitness and high mortality. Such sites, e.g., along roads, show source-sink population dynamics, as observed in some reptiles and birds of prey at roads.

Ecosystem services - Human benefits of ecological functions, divided up in supporting, provisioning, regulating and cultural ecosystem services. Roads can modify existing ecosystem services and create new services.

Ecocline - Changing abiotic conditions along a hydrological, geomorphological, soil or disturbance gradient that determine a coenocline.

Ecotone - Transition ecosystems resulting from interactions between an ecocline and a coenocline.

Edge effect - An ecological concept that describes ecological phenomena occurring at the boundary of two or more adjoining habitats (ecotone). At the population or community level, edge effects are commonly reflected by changes in abundance and diversity of different species in these transition zones, and by the presence of unique species that are not present in either of the boundary habitats.

Endemic species - Native species that exist only in one single defined geographical location or region, and nowhere else in the world.

Eutrophication - The process by which a soil or water body becomes gradually enriched with nutrients and minerals, leading to excessive growth of dominant terrestrial or aquatic plants that outcompete other species and resulting in oxygen-depletion of the water body.

Extinction debt, colonisation debt - Delayed response of communities to altered habitat factors, often found in long-lived, clonal species with poor dispersal and abundant seed bank. Application: Fragmentation effects of new roads increase with time and the benefit of well-designed roadsides takes time.

Functional diversity - Numbers and relative abundance of certain species traits and life forms, e.g., wind-pollinated species, scavengers or endomycorrhizal fungi.

Restoration of roadside habitats should aim at high functional diversity.

Functional species groups - A group of species sharing life-form, roles and functions in a community.

Habitat configuration - Composition of biotic and abiotic elements in a given geographical space.

Habitat disturbance - Impact of a temporary, but sometimes regular or frequent, physical factor that causes a drastic change in an ecosystem. Here used, e.g., for disturbance to the ground by ditching or to vegetation by cutting.

Habitat generalist and specialist - Generalist species can use a variety of resources and thrive in a range of environmental conditions, while specialist species have a more limited diet and narrower niche in which they can thrive.

Habitat fragmentation - Emergence of discontinuities in the suitable environment of a given species.

Habitat stress - Impact of a remaining physical factor that constitute a limitation for species, vegetation etc. Here used, e.g., for nutrient limitation and drought stress.

Hemi-parasitic plant - A green plant having photosynthesis, but that is partially parasitic on shoots and roots of other plants.

Hydrogeological alterations - Changes in distribution and movement of groundwater in the landscape.

Invasive alien species - Non-native species (neophyte, neozoon) that has been introduced out of range by humans, and that causes negative effects on biodiversity and/or ecosystem services (e.g., racoon dog, water hyacinth). These species benefit disproportionally from roadsides.

Keystone species - Species that play a critical role in maintaining the structure and functions of an ecological community.

Landscape history - Here used in the context of land-use history in a landscape, and how the landscape's distribution of various habitats has changed over time.

Landscape matrix - Large-scale area characterised by natural features and embedding a given small-scale area characterised by different natural features.

Land-use intensity - Degree of anthropogenic land use characterising a given geographical space.

Light pollution - Disruptive effects of artificial light on organisms and ecosystems, altering natural light cycles across a range of spatiotemporal scales.

Monitoring – Systematic recording of changes in the abiotic and biotic patterns and processes of naturally disturbed, degraded, restored, or managed ecosystems. It should be followed up by adaptive management.

Mulching - Cutting of vegetation using a machinery that minces the cut material, for example in order to speed up the decomposition and increase the fertilisation of the soil.

Neobiota, neophyte, neozoon - Novel species that were introduced by humans out of range after the beginning of worldwide trade, travel and transport in the 16th century.

Novel ecosystem - Combination of new ecological processes, neobiota or other locally unknown species that profoundly alter the state of an ecosystem, e.g., salinised soils or dominated by cultivars.

Passive vs. active restoration - The former relies mostly on natural processes of succession, e.g., during soil development and colonisation of quarries; the latter uses interventions of site preparation and species introduction to speed up the restoration process.

Pollinator network - Mutualistic interaction relationships between a plant community and its pollinators, usually visualised as connections between species pairs.

Remnant population - Remains of a previously larger population of a species in an area.

Road corridor - Here used for the area that hosts the road and its adjacent ditches, embankments etc., i.e., up to where other land-use takes on.

Road kills - Animals that have been killed on roads following collision with a car or other motor vehicles.

Road-effect zone - Geographical space affected by road impacts.

Roadside management - Planning, design, construction, and maintenance of the primarily vegetated areas along roads.

Seed limitation - Most species show limited dispersal, and dispersal declines with increasing propagule size. Thus, although site conditions in terms of soil and climate might be suitable, the target species do not establish. Sowing, planting or topsoil transfer are methods to alleviate this limitation.

Seed provenance - Depending on the degree of gene flow and of local adaptation, many species show site- or region-specific genetic and phenotypic differentiation that needs to be respected during roadside construction and management to achieve functional communities.

Site limitation - Unsuitable soil, water or climatic conditions of restoration sites that prevent establishment of target communities.

Soil seed bank - The storage of viable but dormant seeds in the soil that can be triggered to germinate. Can refer to the total storage of all species, or to one species.

Sound pollution - The propagation of anthropogenic noise, including e.g., traffic and industrial activities, that impacts biodiversity by altering natural soundscapes.

Species–area relationship - The patterns describing the increase in species number with increasing area of observation.

Steppingstones - Individual habitat patches potentially supporting flow of genes and individuals in a larger fragmented landscape.

Succession - Directional changes over time in the types of plant species occurring in an area, typically towards forest communities.

Target species - A species with important attributes given priority in establishment or management of a community.

Topsoil removal - To reduce negative effects of eutrophication or acidification, topsoil (10-30 cm) is removed in some restoration projects, e.g., to avoid high productivity and respective management costs at roadsides.

Viable population - A population that can persist over time by having a growth rate of 1 (the population size is stable) or higher than 1 (the population size increases).

Annex 2: Examples of use of the Landscape Guidelines

Example 1: Doñana National Park, Spain

We illustrate our stepwise procedure below using an example based on a target area of south-western Spain, namely Doñana National Park. We explain the whole stepwise procedure and provide landscape guidelines for one of the possible landscape combinations.

Step 1: Select from **landscape dichotomies** the landscape features of your target area. Selected landscape features for Doñana National Park are shown below in bold type:

1st dichotomy: **Warm landscapes** vs. Cold landscapes

2nd dichotomy: Snowy or frosty landscapes vs. **Snowless or frostless landscapes**

3rd dichotomy: Humid landscapes vs. **Arid landscapes**

4th dichotomy: Mountains vs. **Flatlands**

5th dichotomy: **Wetlands** vs. **Drylands**

6th dichotomy: **Coastal landscapes** vs. **Inland landscapes**

7th dichotomy: **Forests** vs. **Open land**

8th dichotomy: **Extensive landscapes** vs. **intensive landscapes**

9th dichotomy: **Homogeneous landscapes** vs. **Heterogeneous landscapes**

Note that for four dichotomies (5, 6, 8, 9), the Doñana National Park can be described by both landscape features of a given landscape dichotomy.

Step 2: If the **target area** can be described by both landscape features of a given landscape dichotomy, build a table to quantify the potential number of landscape combinations for your target area.

Table A2.1: All 32 possible landscape combinations (LC) of Doñana National Park. Rows highlighted in grey refer to landscape dichotomies for which both landscape features were selected

LC 1	LC 2	LC 3	LC 4	LC 5	LC 6	LC 7	LC 8	LC 9	LC 10	LC 11	LC 12	LC 13	LC 14	LC 15	LC 16	LC 17	LC 18	LC 19	LC 20	LC 21	LC 22	LC 23	LC 24	LC 25	LC 26	LC 27	LC 28	LC 29	LC 30	LC 31	LC 32
Wa	Wa	Wa	Wa	Wa	Wa	Wa	Wa	Wa	Wa	Wa	Wa	Wa	Wa	Wa	Wa	Wa	Wa	Wa	Wa	Wa	Wa	Wa	Wa	Wa	Wa	Wa	Wa	Wa	Wa	Wa	Wa
SFl	SFl	SFl	SFl	SFl	SFl	SFl	SFl	SFl	SFl	SFl	SFl	SFl	SFl	SFl	SFl	SFl	SFl	SFl	SFl	SFl	SFl	SFl	SFl	SFl	SFl	SFl	SFl	SFl	SFl	SFl	SFl
Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar
Flat	Flat	Flat	Flat	Flat	Flat	Flat	Flat	Flat	Flat	Flat	Flat	Flat	Flat	Flat	Flat	Flat	Flat	Flat	Flat	Flat	Flat	Flat	Flat	Flat	Flat	Flat	Flat	Flat	Flat	Flat	Flat
We	We	We	We	We	We	We	We	We	We	We	We	We	We	We	We	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry
Co	Co	Co	Co	Co	Co	Co	Co	Il	Il	Il	Il	Il	Il	Il	Il	Co	Co	Co	Co	Co	Co	Co	Co	Il	Il	Il	Il	Il	Il	Il	Il
Fo	Fo	Fo	Fo	Ol	Ol	Ol	Ol	Fo	Fo	Fo	Fo	Ol	Ol	Ol	Ol	Fo	Fo	Fo	Fo	Ol	Ol	Ol	Ol	Fo	Fo	Fo	Fo	Ol	Ol	Ol	Ol
Ex	Ex	In	In	Ex	Ex	In	In	Ex	Ex	In	In	Ex	Ex	In	In	Ex	Ex	In	In	Ex	Ex	In	In	Ex	Ex	In	In	Ex	Ex	In	In
Ho	He	Ho	He	Ho	He	Ho	He	Ho	He	Ho	He	Ho	He	Ho	He	Ho	He	Ho	He	Ho	He	Ho	He	Ho	He	Ho	He	Ho	He	Ho	He

Table legend: Wa: Warm landscape; SFl: Snowless or frostless landscape; Ar: Arid landscape; Flat: Flatlands; Co: Coastal landscape; Il: Inland landscape; We: Wetland; Dry: Dryland; Fo: Forest; Ol: Open land; Ex: Extensive landscape; In: Intensive landscape; Ho: Homogeneous landscape; He: Heterogeneous landscape.

Step 3: Select from the table the **landscape combinations** present in the target area.

Table A2.2: Eleven landscape combinations (LC) within the Doñana National Park. Crossed out columns refer to landscape combinations not actually present in the park, while columns highlighted in grey refer to landscape combinations present

~~LC 1~~	~~LC 2~~	~~LC 3~~	~~LC~~ 4	~~LC 5~~	~~LC 6~~	~~LC 7~~	~~LC 8~~	~~LC 9~~	~~LC 10~~	~~LC 11~~	~~LC 12~~	~~LC 13~~	~~LC 14~~	LC 15	~~LC 16~~	LC 17	LC 18	~~LC 19~~	~~LC 20~~	LC 21	LC 22	~~LC 23~~	~~LC 24~~	LC 25	LC 26	LC 27	~~LC 28~~	LC 29	LC 30	LC 31	~~LC 32~~
~~Wa~~	~~Wa~~	~~Wa~~	~~Wa~~	~~Wa~~	~~Wa~~	~~Wa~~	~~Wa~~	~~Wa~~	~~Wa~~	~~Wa~~	~~Wa~~	~~Wa~~	~~Wa~~	Wa	~~Wa~~	Wa	Wa	~~Wa~~	~~Wa~~	Wa	Wa	~~Wa~~	~~Wa~~	Wa	Wa	Wa	~~Wa~~	Wa	Wa	Wa	~~Wa~~
~~SFl~~	~~SFl~~	~~SFl~~	~~SFl~~	~~SFl~~	~~SFl~~	~~SFl~~	~~SFl~~	~~SFl~~	~~SFl~~	~~SFl~~	~~SFl~~	~~SFl~~	~~SFl~~	SFl	~~SFl~~	SFl	SFl	~~SFl~~	~~SFl~~	SFl	SFl	~~SFl~~	~~SFl~~	SFl	SFl	SFl	~~SFl~~	SFl	SFl	SFl	~~SFl~~
~~Ar~~	~~Ar~~	~~Ar~~	~~Ar~~	~~Ar~~	~~Ar~~	~~Ar~~	~~Ar~~	~~Ar~~	~~Ar~~	~~Ar~~	~~Ar~~	~~Ar~~	~~Ar~~	Ar	~~Ar~~	Ar	Ar	~~Ar~~	~~Ar~~	Ar	Ar	~~Ar~~	~~Ar~~	Ar	Ar	Ar	~~Ar~~	Ar	Ar	Ar	~~Ar~~
~~Flat~~	~~Flat~~	~~Flat~~	~~Flat~~	~~Flat~~	~~Flat~~	~~Flat~~	~~Flat~~	~~Flat~~	~~Flat~~	~~Flat~~	~~Flat~~	~~Flat~~	~~Flat~~	Flat	~~Flat~~	Flat	Flat	~~Flat~~	~~Flat~~	Flat	Flat	~~Flat~~	~~Flat~~	Flat	Flat	Flat	~~Flat~~	Flat	Flat	Flat	~~Flat~~
~~We~~	~~We~~	~~We~~	~~We~~	~~We~~	~~We~~	~~We~~	~~We~~	~~We~~	~~We~~	~~We~~	~~We~~	~~We~~	~~We~~	We	~~We~~	Dry	Dry	~~Dry~~	~~Dry~~	Dry	Dry	~~Dry~~	~~Dry~~	Dry	Dry	Dry	~~Dry~~	Dry	Dry	Dry	~~Dry~~
~~Co~~	~~Co~~	~~Co~~	~~Co~~	~~Co~~	~~Co~~	~~Co~~	~~Co~~	~~Il~~	~~Il~~	~~Il~~	~~Il~~	~~Il~~	~~Il~~	Il	~~Il~~	Co	Co	~~Co~~	~~Co~~	Co	Co	~~Co~~	~~Co~~	Il	Il	Il	~~Il~~	Il	Il	Il	~~Il~~
~~Fo~~	~~Fo~~	~~Fo~~	~~Fo~~	~~Ol~~	~~Ol~~	~~Ol~~	~~Ol~~	~~Fo~~	~~Fo~~	~~Fo~~	~~Fo~~	~~Ol~~	~~Ol~~	Ol	~~Ol~~	Fo	Fo	~~Fo~~	~~Fo~~	Ol	Ol	~~Ol~~	~~Ol~~	Fo	Fo	Fo	~~Fo~~	Ol	Ol	Ol	~~Ol~~
~~Ex~~	~~Ex~~	~~In~~	~~In~~	~~Ex~~	~~Ex~~	~~In~~	~~In~~	~~Ex~~	~~Ex~~	~~In~~	~~In~~	~~Ex~~	~~Ex~~	In	~~In~~	Ex	Ex	~~In~~	~~In~~	Ex	Ex	~~In~~	~~In~~	Ex	Ex	In	~~In~~	Ex	Ex	In	~~In~~
~~Ho~~	~~He~~	~~Ho~~	~~He~~	~~Ho~~	~~He~~	~~Ho~~	~~He~~	~~Ho~~	~~He~~	~~Ho~~	~~He~~	~~Ho~~	~~He~~	Ho	~~He~~	Ho	He	~~Ho~~	~~He~~	Ho	He	~~Ho~~	~~He~~	Ho	He	Ho	~~He~~	Ho	He	Ho	~~He~~

Table legend: Wa: Warm landscape; SFl: Snowless or frostless landscape; Ar: Arid landscape; Flat: Flatlands; Co: Coastal landscape; Il: Inland landscape; We: Wetland; Dry: Dryland; Fo: Forest; Ol: Open land; Ex: Extensive landscape; In: Intensive landscape; Ho: Homogeneous landscape; He: Heterogeneous landscape.

Step 4: Select the **corresponding guidelines** for each landscape combination of the target area.

Our stepwise procedure, together with our local knowledge of the target area, highlighted that Doñana National Park includes ten different landscape combinations. For example, the 15th landscape combination (LC15) refers to areas composed of these landscape features: Warm landscape, Snowless or frostless landscape, Arid landscape, Flatland, Wetland, Inland landscape, Open land, Intensive landscape and Homogeneous landscape. Consequently, the guidelines to be implemented for this landscape combination will be:

Warm landscapes

- Rocky outcrops, sand or gravel patches should be provided along roadside habitats in order to limit ***road-kill*** of insects and reptiles by attracting basking activity usually performed on the road.
- Early detection and rapid response (EDRR) to ***biological invasions*** are recommended, especially under high-traffic scenarios. In order to prevent colonisation by invasive species, the biotic resistance of roadside vegetation should be promoted (see also *Habitat guidelines*).

Arid landscapes

- Concerning ***fragmentation***, microclimatic conditions that increase roadside moisture should be promoted, in order to host higher densities of surrounding species (especially in low-traffic scenarios).
- Concerning ***hydrogeological alterations***, erosion and landslides can be limited by establishing deep-rooted native vegetation on roadsides.

Flatlands

- EDRR and biotic resistance to ***biological invasions*** should be prioritised.
- In order to limit ***light pollution***, streetlamps should not be installed (where possible) or at least should be mitigated by choosing less-impacting light sources (e.g. sodium lamps), directional lights focused on the road, and timed or intelligent (i.e. with movement sensors) road lighting. The negative effects of

streetlamps (and headlights in high-traffic scenarios) should be mitigated by establishing native trees and shrubs on both roadsides.
- In order to limit ***noise pollution***, native shrubs and artificial barriers should be established on both roadsides, especially in high-traffic scenarios.

Wetlands

- The ***road-kill*** of small vertebrates (especially amphibians and reptiles) can be mitigated by establishing drift fences along roads. Drift fence effectiveness should be ensured by vegetation maintenance or, even better, by establishing native (short) grasslands at roadsides. Barrier effects will increase and should be compensated for by wildlife road-crossing structures.
- Populations of semi-aquatic species suffering natural and artificial ***fragmentation*** can be connected by establishing stepping-stone ponds along roadsides. In low-traffic scenarios, conservation-concern species can be established, whereas in high-traffic scenarios common native species can be preferred, preferably providing ecosystem services and potentially unaffected by ecological traps.
- EDRR and biotic resistance to ***biological invasions*** should be prioritised.
- In order to limit ***light pollution***, streetlamps should not be installed (where possible) or at least should be mitigated.

Open lands

- In the case of fragmented natural open land, ***fragmentation*** for local species can be reduced by establishing stepping-stone habitats along roadsides, in order to connect fragmented patches (for selecting species to be established, the same concepts see Flatlands should be applied).
- EDRR and biotic resistance to ***biological invasions***.
- In order to limit ***light pollution***, street lamps should not be installed (where possible) or at least should be mitigated.
- In high-traffic scenarios, native shrubs and artificial barriers are needed on both sides of the road to reduce ***noise pollution***.

Intensive landscapes

- In order to reduce ***road-kills***, wildlife road-crossing structures should be provided in conjunction with natural wildlife corridors.
- In the case of ***fragmentation***, isolated populations of local species can be connected by establishing stepping-stone habitats at roadsides.
- EDRR and biotic resistance to ***biological invasions*** should be prioritised.
- In order to limit ***light pollution***, streetlamps should not be installed (where possible) or at least should be mitigated.
- In high-traffic scenarios, native shrubs and artificial barriers should be established on both sides of the road to reduce ***noise pollution***.
- In high-traffic scenarios, the potential impact of ***chemical pollution*** should be limited by avoiding promoting conservation-concern species on roadsides.

Homogeneous landscapes

- In order to limit ***road-kills***, wildlife road-crossing structures should be provided in natural wildlife corridors.
- EDRR and biotic resistance to ***biological invasions*** should be prioritised.

The 15th landscape combination of Doñana Natural Park comprises large areas of rice fields in the inland part of the protected area. This area has few major roads connecting local villages (high-traffic scenario), and many minor roads (low-traffic scenario). All these roads cross areas flooded by water, mainly seasonally. Most roadsides are steep slopes a few metres in extent. The suggested guidelines for this landscape combination concern road-kills (4 mentions), habitat fragmentation and connectivity (4 mentions), biological invasions (6 mentions), light pollution (4 mentions), noise pollution (3 mentions), chemical pollution (1 mention) and hydrogeological alterations (1 mention). As a consequence, biological invasions are a major concern in this area. Light pollution could also be a relevant concern in this kind of area, but we know that local roads have no streetlamps, so we can ignore related guidelines. Road-kills, habitat fragmentation and connectivity, and noise pollution have 3-4 mentions. Road-kills should be seriously considered, whereas fragmentation is not a major issue in these homogeneous marshes, and noise pollution is a concern only on major roads. Chemical pollution and hydrogeological alterations are less reported topics for this landscape combination, but the former can be a major concern along high-traffic roads, and the latter is an issue of paramount importance in wetlands. Considering our knowledge of this target area, the reduced set of guidelines for this landscape combination will be (in order of relevance):

- EDRR to ***biological invasions*** are recommended, especially under high-traffic scenarios. In order to prevent colonisation by invasive species, the biotic resistance of roadside vegetation should be promoted (see *Habitat guidelines*).
- In order to reduce **road-kills**, provide wildlife road-crossing structures at natural wildlife corridors. The road-kill of insects and reptiles can be mitigated by providing basking stones along roadsides. The road-kill of small vertebrates (especially amphibians and reptiles) can be mitigated by establishing drift fences in the transition areas between lands and water. Drift-fence effectiveness should be ensured by vegetation maintenance or, even better, by establishing native (short) grassland on roadsides.
- In high-traffic scenarios, establish native shrubs and artificial barriers on both sides of the road to reduce **noise pollution**.
- In high-traffic scenarios, the negative effects of **chemical pollution** should be limited by avoiding promoting conservation-concern species along roadsides.
- Concerning **hydrogeological alterations**, both erosion and landslides can be limited by establishing deep-rooted native vegetation on roadsides.

As a consequence of these landscape guidelines, the roadsides of this landscape combination in Doñana National Park should host native shortgrass species (in order to ensure the effectiveness of drift fences) and native shrubs (especially along high-traffic roads, in order to limit noise pollution). The tamarisks (*Tamarix* spp.) are good candidates as roadside shrubs. There are different tamarisk species in Doñana, already present on many local roadsides. They are suitable for hosting many arthropod species and even the nesting or roosting of several bird species (both passerines and waterbirds, such as the black-crowned night heron *Nycticorax nycticorax* and the glossy ibis *Plegadis falcinellus*, which usually avoid high-traffic roads). For both shortgrass and shrubs, deep-rooted species would be the best choice (in order to limit erosion and landslides). The presence of conservation-concern vegetation, such as the Critically Endangered *Cheirolophus uliginosus* (an endemic centaury of south-western Spain), which is already present in some roadsides in Doñana, can be promoted in low-traffic roadsides. On the other hand, in order to limit the impact of chemical pollution, the presence of conservation-concern vegetation should be avoided in high-traffic roadsides, where common native species can be established, preferably selecting species providing ecosystem services and potentially unaffected by ecological traps. In order to reduce road-kills, wildlife road-crossing structures (especially underpasses focused on amphibians and reptiles) and drift fences should be established at least in the transition areas between land and water. Doñana National Park hosts a diverse community of amphibians, including some species globally endangered and still relatively common in this protected area, such as the western spadefoot toad *Pelobates cultripes*. Where drift fences cannot be established, providing basking stones in roadsides can reduce the road-kill rates of some reptiles, e.g. viperine water snake *Natrix maura* and Andalusian wall lizard *Podarcis vaucheri*.

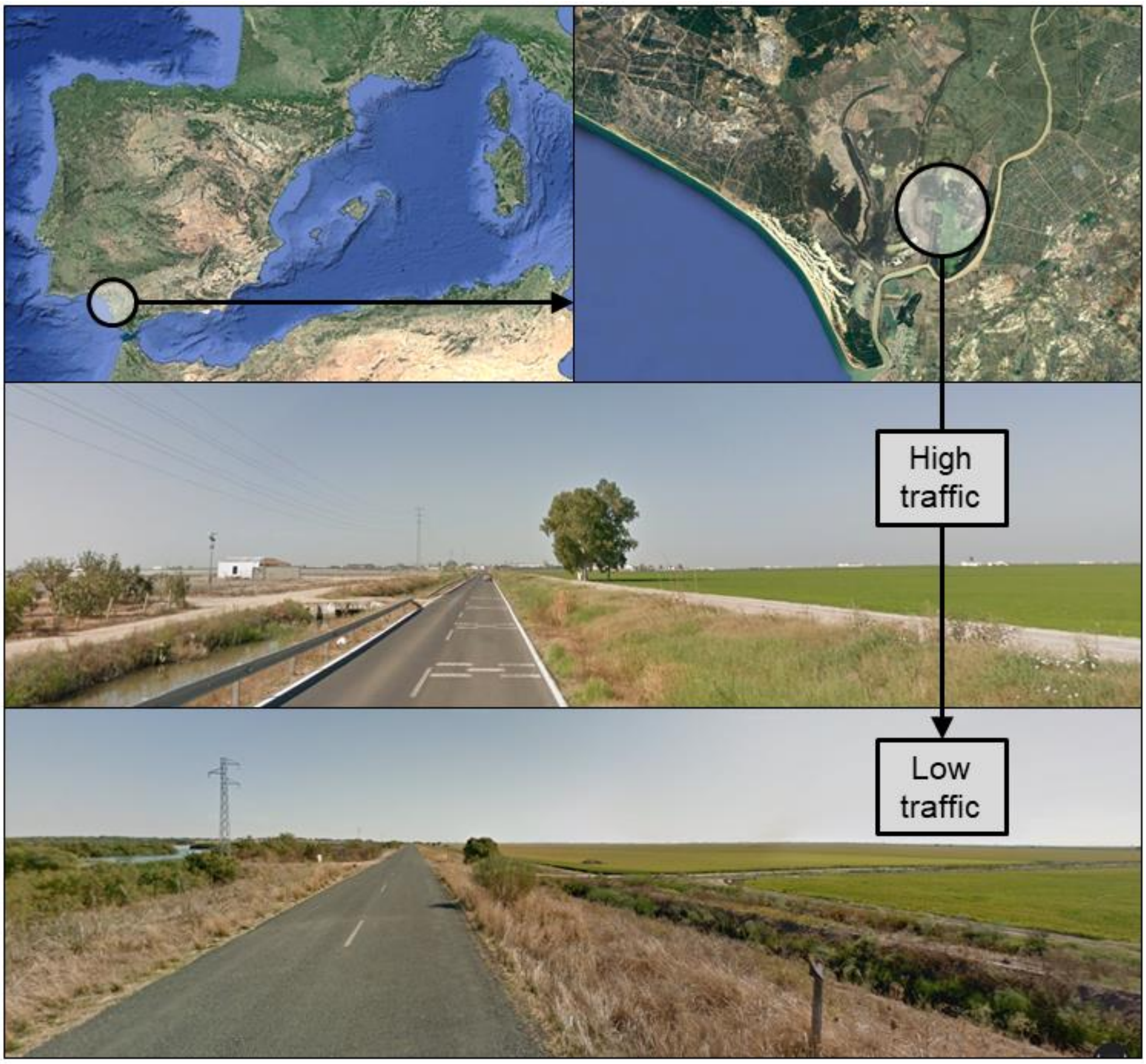


Figure A2.1: In the upper left, the location of case-study area (Doñana National Park) within the Iberian Peninsula. In the upper right, the location of case-study landscape combination (15th, see Table A2.2), including high- and low-traffic scenarios, within Doñana National Park.

Example 2: Small road, forested landscape, Scandinavia

For demonstration, we selected a short road stretch off local road 181 from Løkker to Eidsvoll in Norway. The area comprises an inland, primarily forested landscape, with small hills and flat areas with continuous conifer forest or peatlands and some cattle-based agriculture and urban developments (Figure A2.2A). Forest productivity range from low on shallow soils to high on deeper soils, while peatlands are mainly on deep peat. Land use intensity range from high (agriculture, urbanisations) to low (semi-natural and natural systems) (Figure A2.2B). There is a moderate density of red-listed species or other species of conservation concern, mainly in the peatlands (Figure A2.2C). Sampling intensity behind these numbers is not known. There is a protected forest patch in a ravine and steep slope and a longer stretch of protected wetlands for birds along the road corridor. The density of invasive alien species is low and mainly located in urbanised areas.

Steps 1–3: Select from **landscape dichotomies** the landscape features of the target area. Following the dichotomous key, the area is overall 1 Cold, 2 Snowy, 3 Humid, 4 Flatlands, 6 Inland, and 9 Heterogeneous with split combinations of

5	7	8	Type	Code
Wet	Open	Extensive	Bogs and fens	5W7O8E
Wet	Forest	Extensive	Forest peatland	5W7F8E
Dry	Forest	Extensive	Coniferous forest	5D7F8E
Dry	Open	Intensive	Agriculture	5D7O8I

Step 4: Select the **corresponding guidelines** for each landscape combination of the target area.

Based on these categories, the main challenges will be to:

- Prevent changes to the hydrology of the wetlands;
- Ensure free movement of organisms under bridges where the road crosses streams and wetlands;
- Prevent road-kills of large mammals through e.g. design and maintenance of forest edges and identification of land use patterns during winter;
- Provide connectivity for the forest organisms across the road through a combination of wet channels for amphibians and dry crossing structures for others (based on planned traffic volume);
- Reduce light pollution during the active periods of forest and wetland bats;
- Limit the use of chloride based de-icing to prevent changes to wetland chemistry (with the side effect of attracting less ungulates to the road during winter); and
- In urban and agricultural landscapes, create roadside habitats based on local species that can favour grassland biodiversity and connect these to existing patches when feasible.

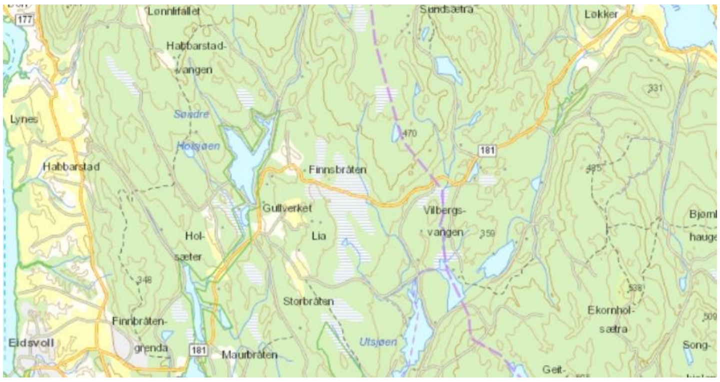


Figure A2.2A: General map showing the road corridor along road 181, urban and agricultural areas (yellow), forest (green) and peatlands or wetlands (light, hatched). Norwegian Environment Agency, Naturbase

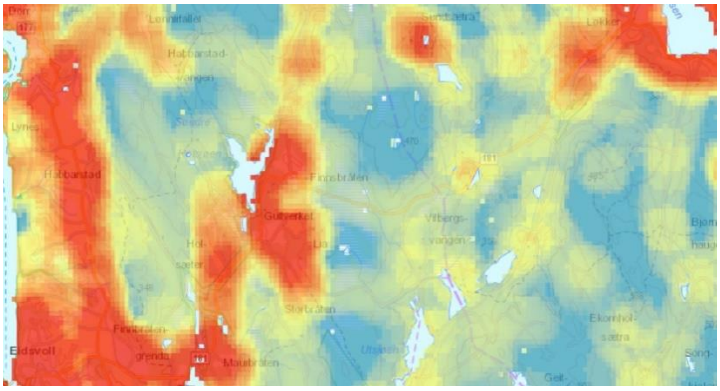


Figure A2.2B: Heatmap of land use intensity, from high intensity (red; urban and agricultural) to low intensity (blue; natural systems). Norwegian Environment Agency, Naturbase

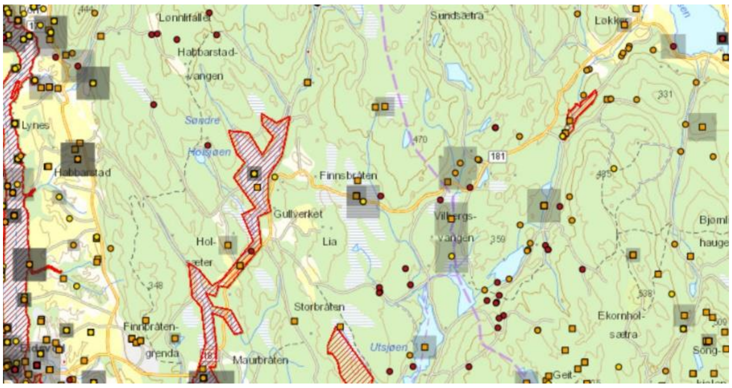


Figure A2.2C: Protected areas (red, hatched) and occurrence of red listed species in the area. Norwegian Environment Agency, Naturbase